Conceptual Model: Capitan Reef Complex Aquifer of Texas

Report

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EXECUTIVE SUMMARY

The Capitan Reef Complex Aquifer is a minor aquifer located in the Trans-Pecos area of western Texas and southeastern New Mexico. The aquifer occurs in a horseshoe-shaped band of carbonate rocks exposed at the land surface or buried beneath younger sediments. The area of primary interest in this project is the eastern arm of the Capitan Reef Complex, extending from Brewster County through Pecos, Ward and Winkler counties in Texas to Lea County and part of Eddy County in New Mexico. This report documents the development of a conceptual model focusing primarily on the eastern arm of the Capitan Reef Complex Aquifer. We have selected the eastern arm of the Capitan Reef Complex Aquifer because part of the western arm of the Capitan Reef Complex is already included in the groundwater flow model for the Bone Spring-Victorio Peak Aquifer by Hutchison (2008).

The Capitan Reef Complex Aquifer consists of the stratigraphic units of the Capitan Reef Complex that were deposited along the margins of the Delaware Basin. These stratigraphic units include the Carlsbad and Capitan limestones, the Goat Seep Dolomite, and the Tessey and Vidrio formations. The aquifer crops out in Brewster, Culberson, Hudspeth, and Pecos counties in Texas and in Eddy County in New Mexico. These outcrops coincide with areas of uplift that resulted in the formation of the Guadalupe, Apache, and Glass mountains. The Capitan Reef Complex Aquifer also occurs in subcrop in parts of Jeff Davis, Pecos, Reeves, Ward, and Winkler counties in Texas and Lea County in New Mexico. The Capitan Reef Complex Aquifer generally dips towards the north and east. This is partially due to uplift that resulted in the formation of the previously mentioned mountain ranges that are located on the western and southern portions of the reef.

Available water level data show that groundwater flow in the Capitan Reef Complex Aquifer occurs parallel to the reef trends. Groundwater generally flows away from aquifer outcrop recharge zones towards deeper parts of the aquifer. Groundwater in the Capitan Reef Complex Aquifer likely discharges by cross-formational flow through overlying stratigraphic units. Discharge by any other mechanism is highly unlikely considering: (1) the lack of contact between the Capitan Reef Complex Aquifer and any surface water bodies, such as, springs and rivers, and (2) the occurrence of artesian wells and water levels higher than those in overlying aquifers suggesting upward hydraulic gradients, especially in the eastern part of the aquifer.

Groundwater in the Capitan Reef Complex Aquifer is used primarily for oil and gas production in the northern and eastern parts of the aquifer, but locally is also used for livestock and irrigation. Sparse multi-year water-level data indicates static, declining, and fluctuating water levels in different parts of the Capitan Reef Complex Aquifer.

There is a general lack of hydraulic property data for the Capitan Reef Complex Aquifer. However, the data available show significant variability in the aquifer properties resulting from structural complexity within the basin, variability in lithology, and the effects of postdepositional processes including karstification. Hydraulic conductivity values for the Capitan Reef Complex range from less than 0.01 feet per day to more than 500 feet per day and display no apparent spatial trends. The median hydraulic conductivity of the Capitan Reef Complex Aquifer is orders of magnitude higher than that of the adjacent basin and shelf stratigraphic units.

Water quality in the Capitan Reef Complex Aquifer is generally brackish to saline, although fresh water occurs in or adjacent to aquifer outcrops. In the subcrop, groundwater ranges from brackish to saline, with the highest salinity in the deepest parts of the aquifer—in Ward County. Capitan Reef Complex Aquifer groundwater compositions range from calcium-magnesium-bicarbonate compositions to calcium-magnesium-sulfate compositions to sodium-chloride compositions, reflecting interaction with minerals—calcite, dolomite, gypsum, and halite—that occur within the Capitan Reef Complex and adjacent stratigraphic units.

Compositions of various isotopes in Capitan Reef Complex Aquifer groundwater indicate that: (1) most recharge to the aquifer occurs in the Guadalupe Mountains and Glass Mountains aquifer outcrops, (2) relatively little recharge occurs in the Apache Mountains outcrop, and (3) evidence of rapid recharge to subcrop parts of the aquifer occurs south of the Delaware Mountains. Additionally, isotopes indicate that recharge to the Capitan Reef Complex Aquifer occurs under a wider range of altitude and climatic conditions in the western arm of the Capitan Reef Complex Aquifer than in the eastern arm. The data suggests that the groundwater flow system in the eastern arm of the aquifer is simpler with a single recharge zone—the Glass Mountains aquifer outcrop.

The conceptual model of the eastern arm of the Capitan Reef Complex Aquifer is a simplified representation of the hydrogeological features—hydrostratigraphy, hydraulic properties, hydraulic boundaries, recharge, and discharge—that influence groundwater flow through the aquifer. The conceptual model for the eastern arm of the Capitan Reef Complex Aquifer—the basis used to construct a groundwater flow model—is composed of up to five model layers simulating groundwater flow through the Capitan Reef Complex Aquifer and overlying aquifers and confining units that occur within the Monument Draw Trough. This conceptual model is characterized by recharge to the aquifer outcrop in the Glass Mountains and limited inflow from the north margin the modeled area, groundwater flow into subcrop parts of the Capitan Reef Complex Aquifer, and discharge by upward flow through overlying aquifers.

1.0 INTRODUCTION

The Capitan Reef Complex Aquifer is a minor aquifer, one of nine major and twenty one minor aquifers in Texas (Figures 1.0.1 and 1.0.2). The Texas Water Development Board defines a major aquifer as an aquifer that produces large amounts of water over a large area, and minor aquifers as aquifers that produce minor amounts of water over large areas or large amounts of water over small areas (George and others, 2011). The Capitan Reef Complex Aquifer meets the definition of a minor aquifer because (1) most of its extent is overlain by major aquifers—such as the Pecos Valley and Edwards-Trinity (Plateau) aquifers— that are more attractive to well drilling due to shallower depth, (2) it underlies a relatively small area that has a small population and little irrigation, and (3) poor water quality make it unattractive for most water uses—historically it has been used for secondary recovery by the petroleum industry (White, 1987). Total pumping from the Capitan Reef Complex Aquifer has ranged from a high of more than 15,000 acre-feet per year to less than 200 acre-feet per year. This aquifer is important because drawdown in overlying major aquifers—especially the Pecos Valley Aquifer—can induce upward groundwater flow from the underlying aquifers such as the Capitan Reef Complex Aquifer (Jones, 2004). The Capitan Reef Complex Aquifer is also becoming more important as use of desalinated groundwater increases its potential as a groundwater source.

This report describes the aquifer data used to develop a conceptual model for the Capitan Reef Complex Aquifer. This conceptual model will be the basis for the construction of a groundwater availability model for the Capitan Reef Complex Aquifer. Once this model is calibrated, it can be used as a quantitative tool to evaluate the effects of pumping, drought, and different water management scenarios on the groundwater flow system. This report includes descriptions of (1) the study area, (2) previous investigations of the Capitan Reef Complex Aquifer, (3) the hydrogeologic setting including hydrostratigraphy, geologic framework, groundwater hydrology, recharge, discharge, surface water, hydraulic properties, and water quality, and (4) the resultant conceptual model.

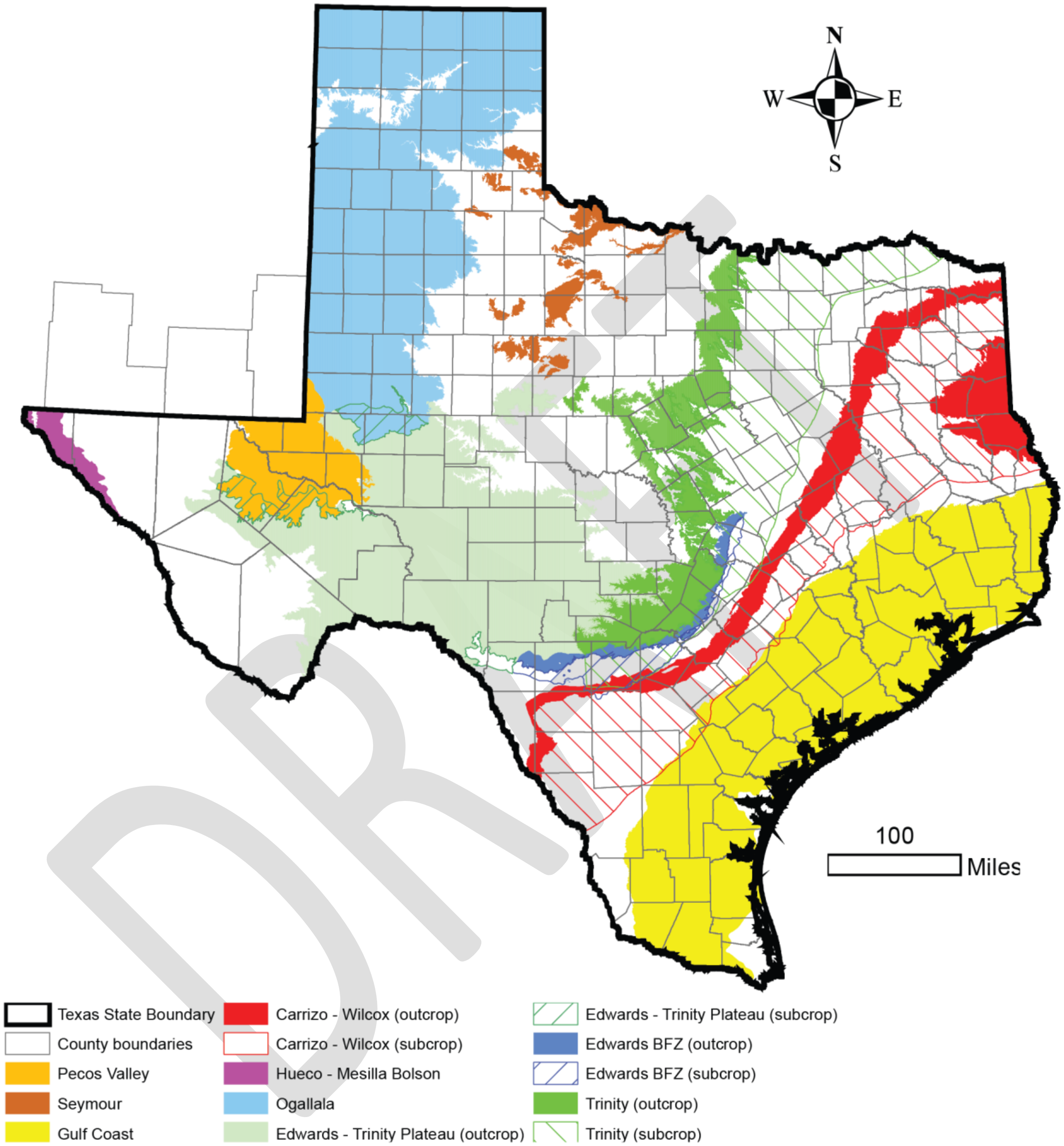


Figure 1.0.1 Locations of major aquifers in Texas.

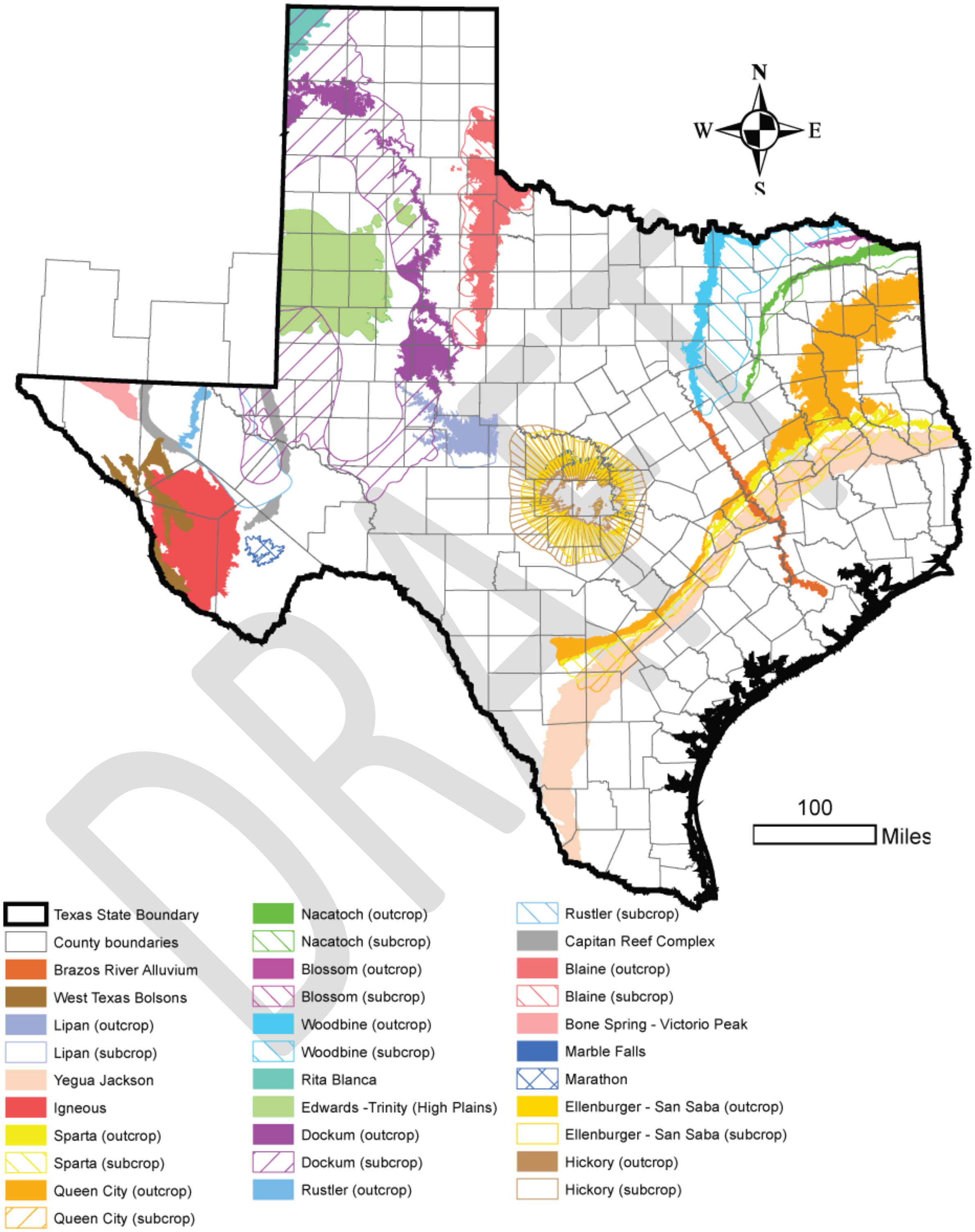


Figure 1.0.2 Locations of minor aquifers in Texas.

2.0 STUDY AREA

The Capitan Reef Complex Aquifer occurs in outcrop and subcrop in a relatively narrow horseshoe-shaped band in the Trans-Pecos area of west Texas and southeastern New Mexico (Figure 2.0.1). The outcrops are located in the Guadalupe, Apache, and Glass mountains (Figure 2.0.2). The Capitan Reef Complex Aquifer boundaries used in this study were defined by work by Standen and others (2009) and are referred to as the alternate (DBSA) boundaries. These boundaries differ from the aquifer boundaries defined by the Texas Water Development Board (Figure 2.0.2). The alternate (DBSA) boundaries are used in this study because they are based on the most up-to-date data with regards to the spatial distribution of the Capitan Reef Complex.

Figure 2.0.3 shows the counties, major roadways, and cities in the study area. The Capitan Reef Complex Aquifer underlies eight counties in Texas and three counties in New Mexico. Cities overlying the Capitan Reef Complex Aquifer include Carlsbad in New Mexico, and Fort Stockton, Kermit, Monahans, Pyote, Wickett, and Wink in Texas. The locations of rivers, streams, lakes, and reservoirs in the study area are shown on Figure 2.0.4. The Pecos River and a few of its tributaries are the only perennial streams in the study area. The Pecos River—where it flows over Capitan Reef Complex Aquifer outcrops near Carlsbad, New Mexico—is the only perennial stream that interacts with of the Capitan Reef Complex Aquifer.

Figures 2.0.5 and 2.0.6 show the major and minor aquifers that occur within the study area. Major aquifers occurring in the study area include parts of the Pecos Valley and Edwards-Trinity (Plateau) aquifers. In addition to the Capitan Reef Complex Aquifer, minor aquifers located in the study area include parts of the Dockum, Igneous, Rustler, and West Texas Bolsons aquifers.

The Capitan Reef Complex Aquifer underlies part of the Far West Texas Regional Water Planning Area and the Region F Regional Water Planning Area (Figure 2.0.7). The aquifer also underlies parts of the Middle Pecos Groundwater Conservation District, Brewster County Groundwater Conservation District, Jeff Davis County Underground Water Conservation District, and Culberson County Groundwater Conservation District (Figure 2.0.8). The Capitan Reef Complex Aquifer underlies portions of Groundwater Management Areas 3, 4, and 7 (Figure 2.0.9). The Capitan Reef Complex Aquifer does not occur within the boundaries of any river authority.

The Capitan Reef Complex Aquifer is contained wholly within the Rio Grande River basin (Figure 2.0.10). For all but the Pecos River and a few of its larger tributaries, rivers and streams in the study area are normally dry. When flow does occur in the smaller rivers and streams, it rarely reaches the Pecos River but rather seeps into the channel beds or spreads out over broad valleys (Ashworth, 1990).

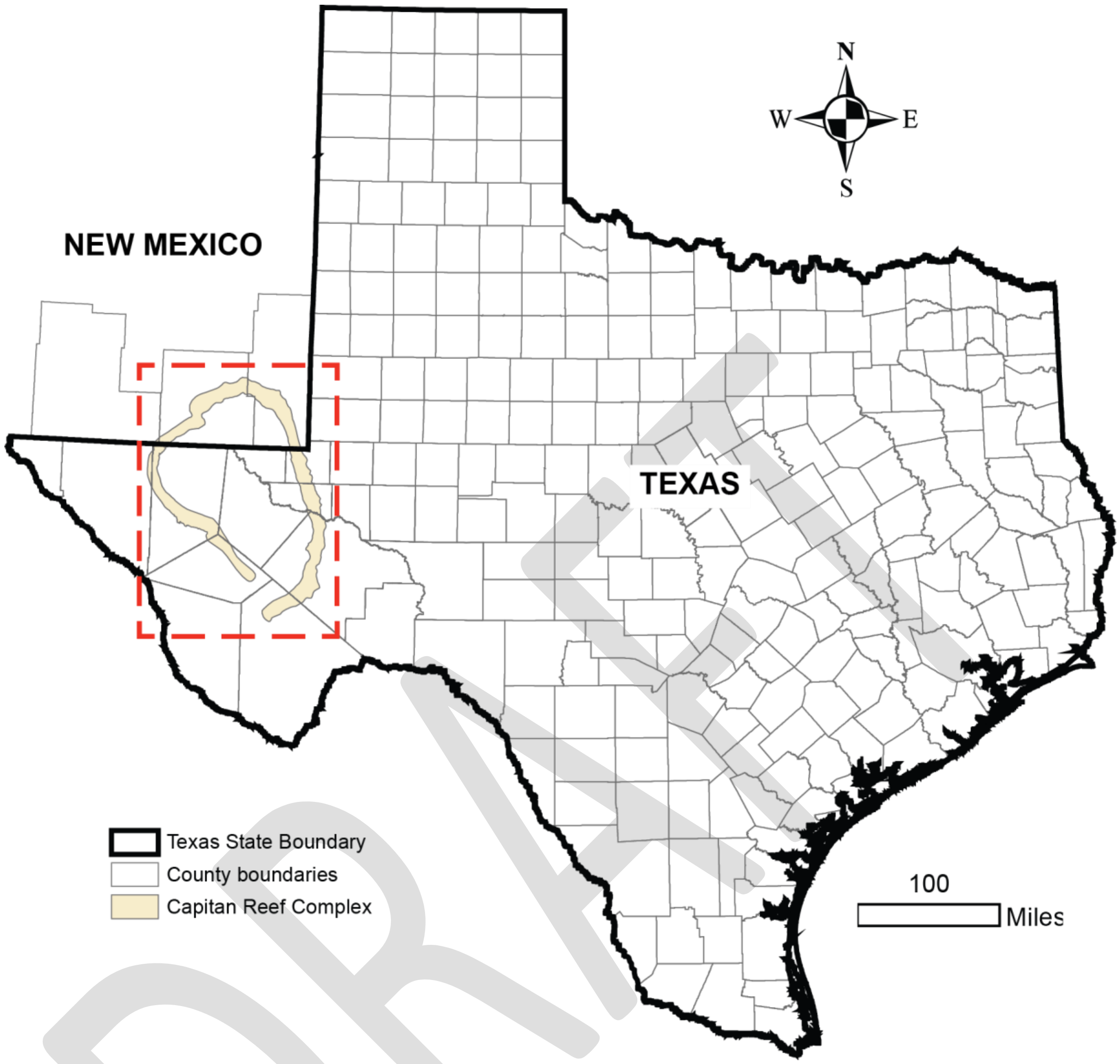


Figure 2.0.1 Study area for the Capitan Reef Complex Aquifer. Aquifer boundaries are based on work by Standen and others (2009).

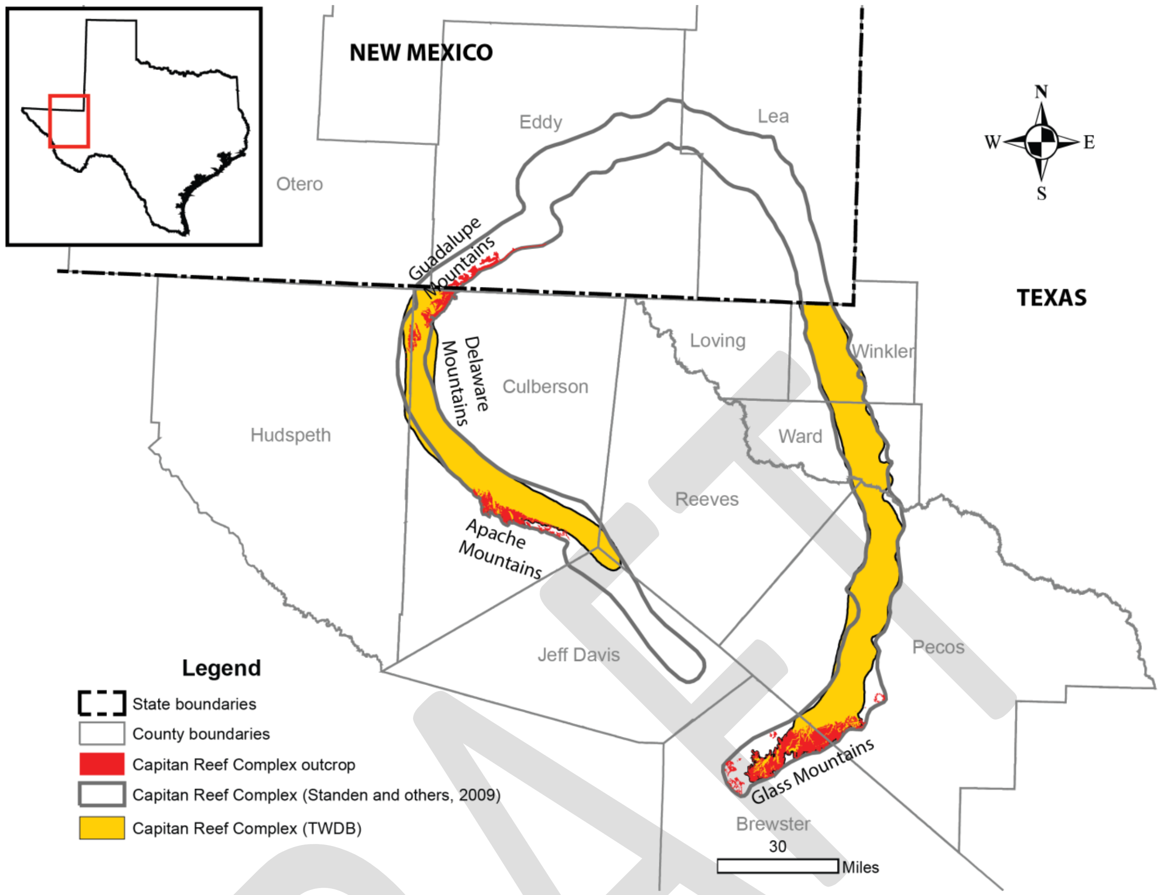


Figure 2.0.2 The official (TWDB) and alternative boundaries of the Capitan Reef Complex Aquifer based on work done by Standen and others (2009) including the location of key mountain ranges in the study area

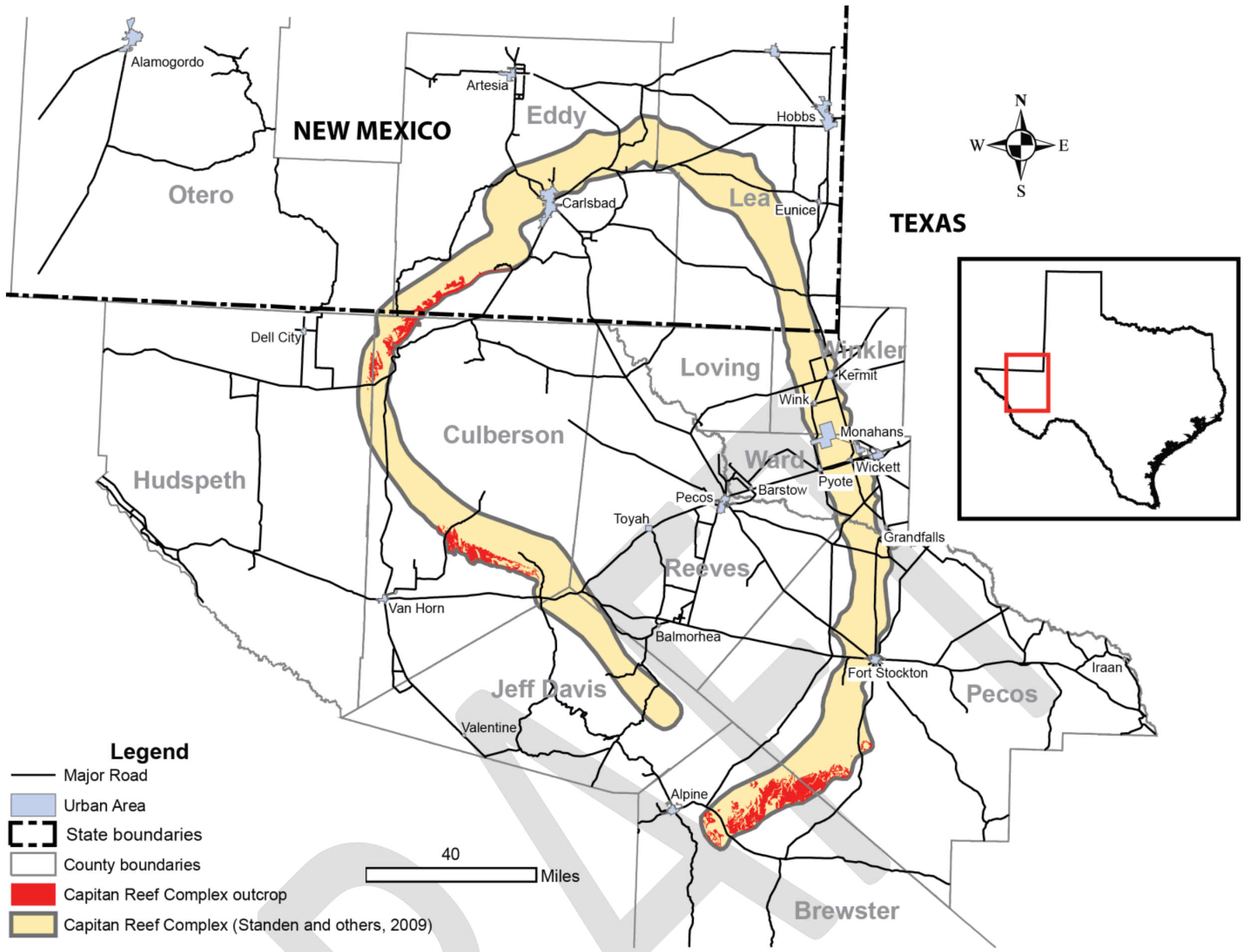


Figure 2.0.3 Cities and major roadways in the study area.

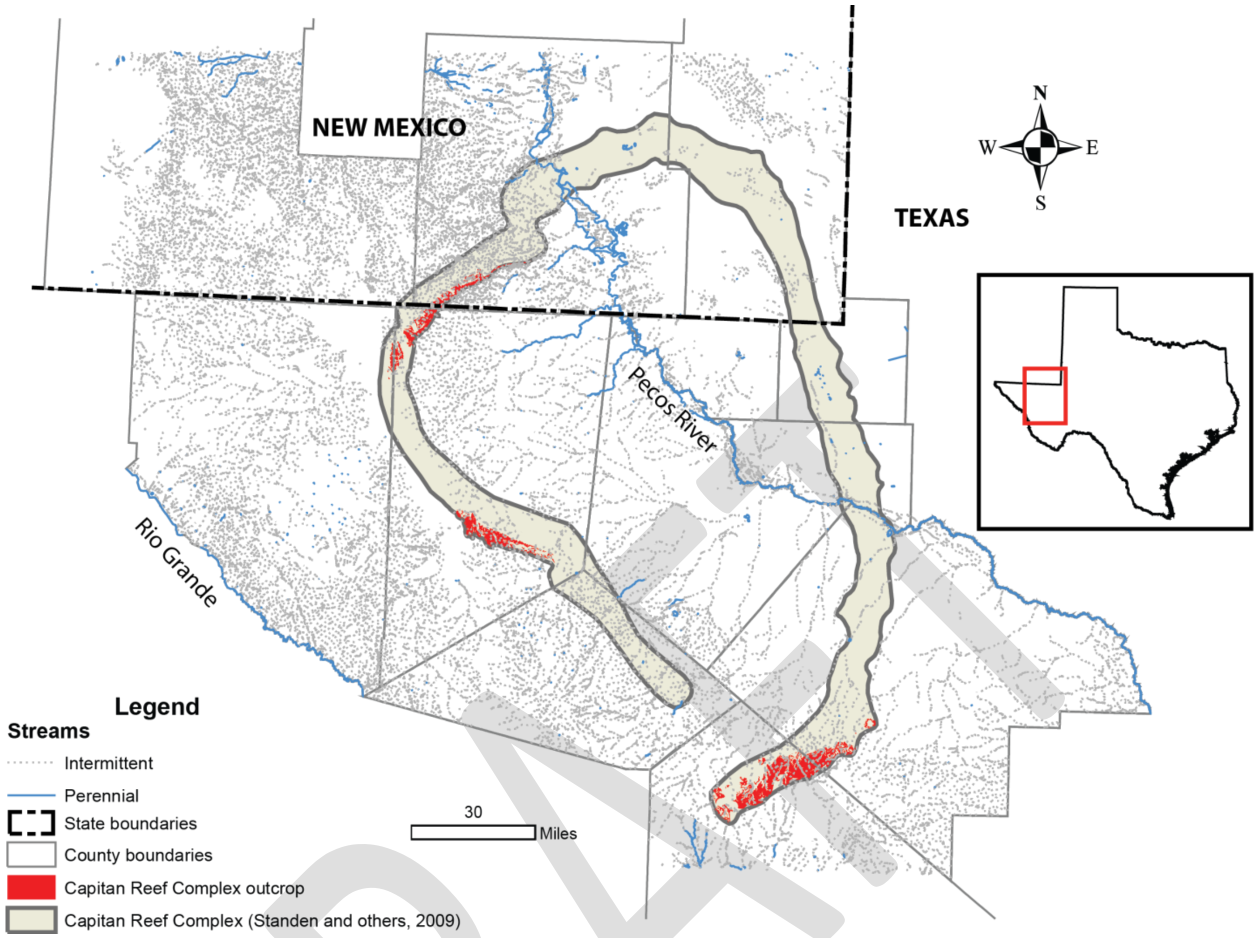


Figure 2.0.4 Rivers, streams, lakes, and reservoirs in the study area.

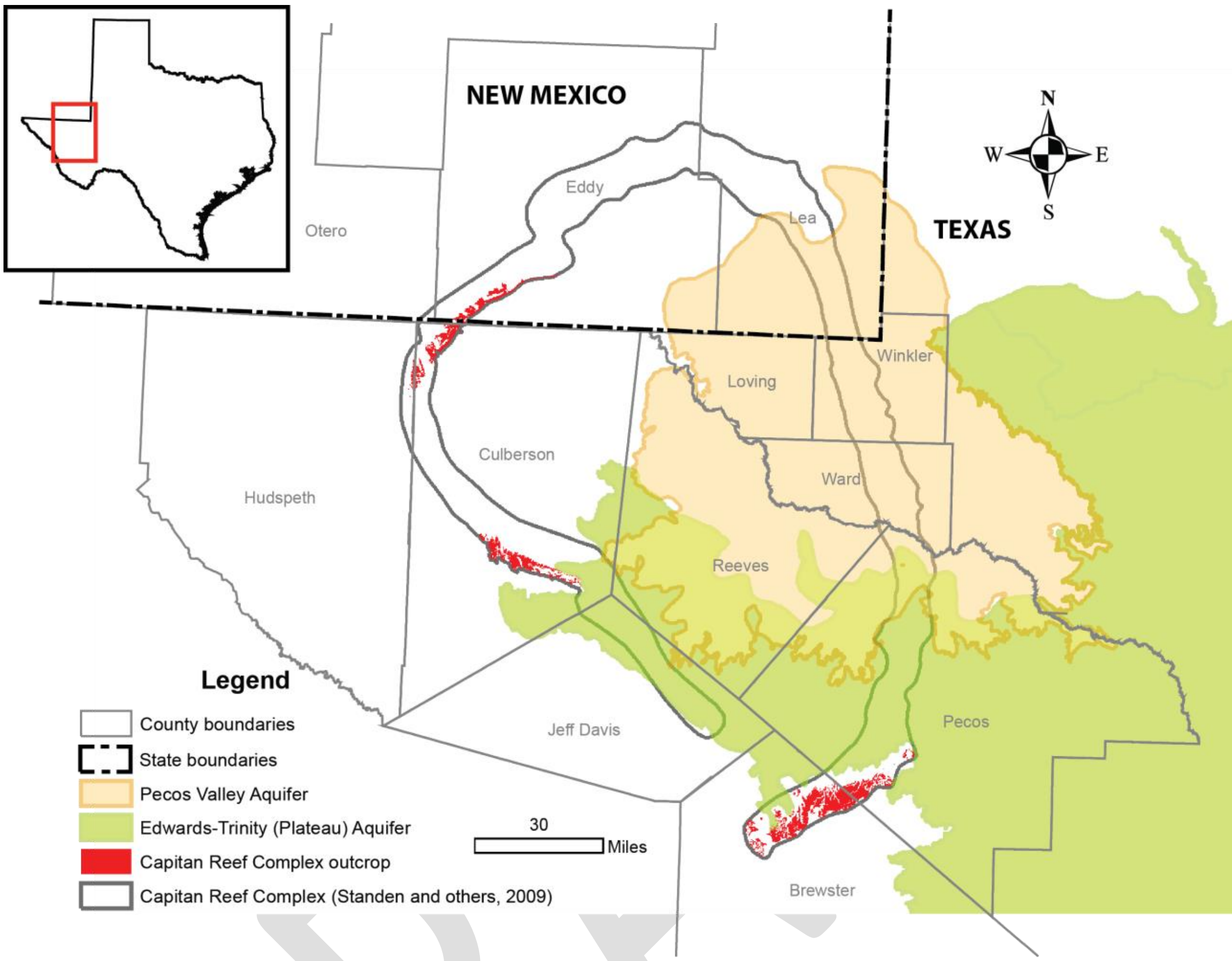


Figure 2.0.5 Major aquifers in the study area.

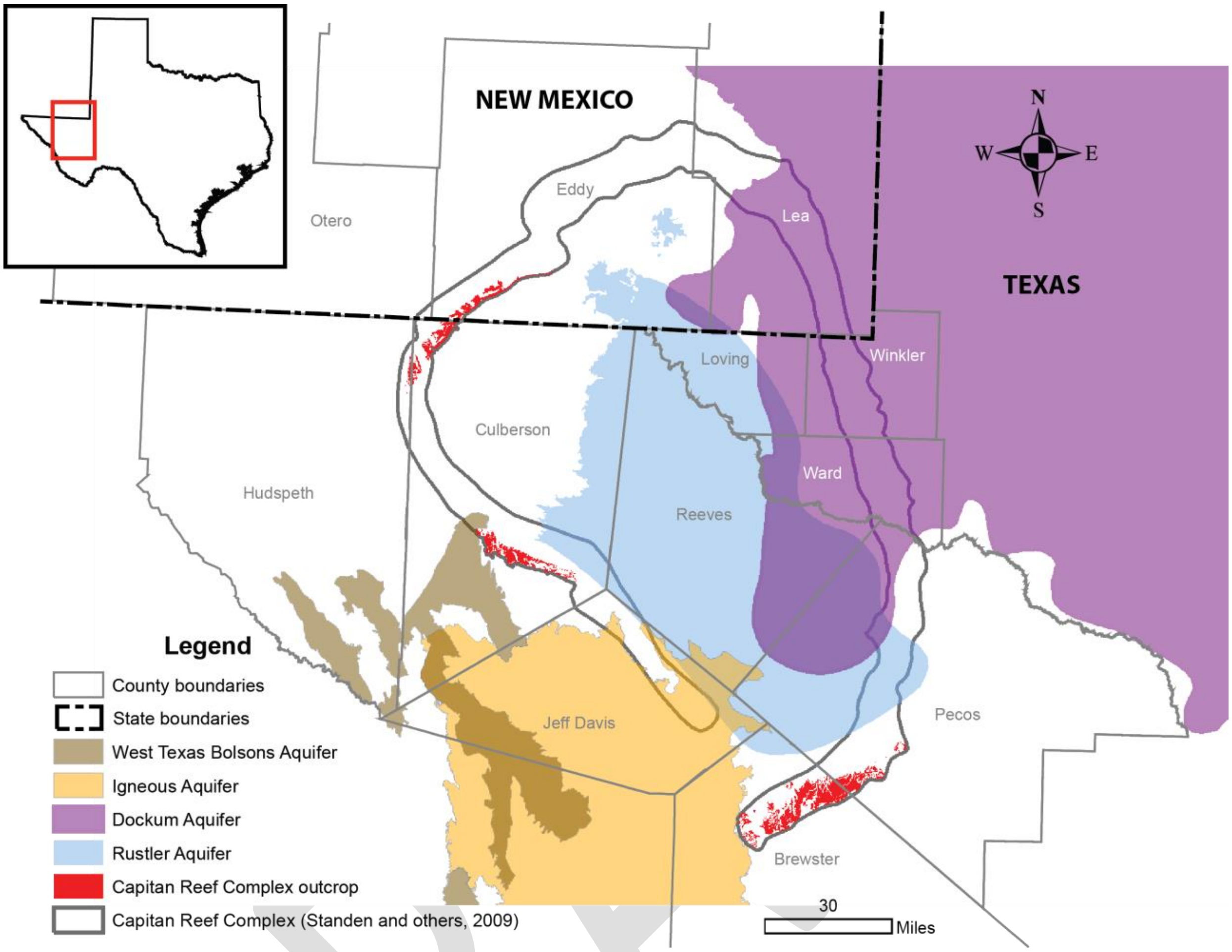


Figure 2.0.6 Minor aquifers in the study area.

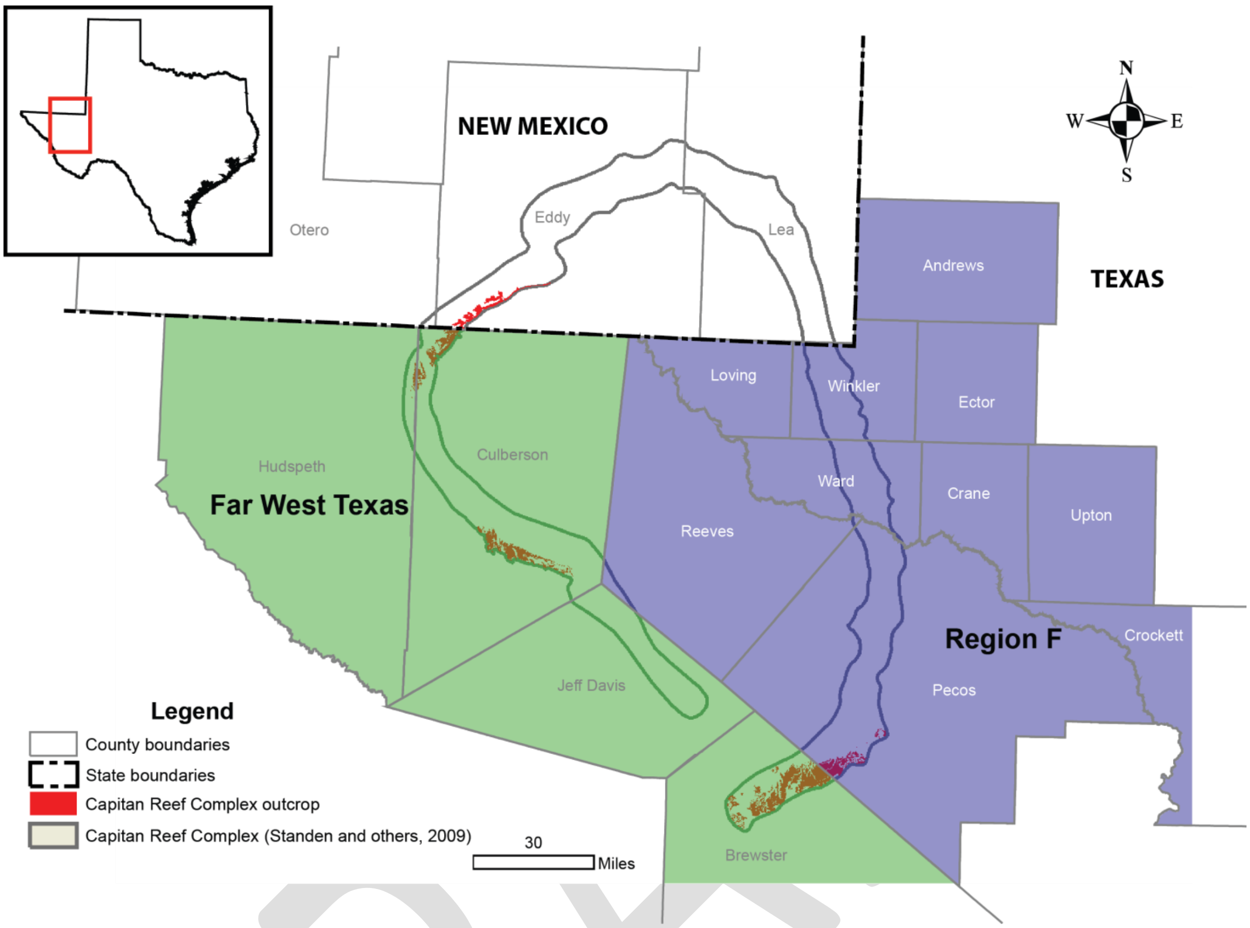


Figure 2.0.7 Texas regional water planning areas in the study area.

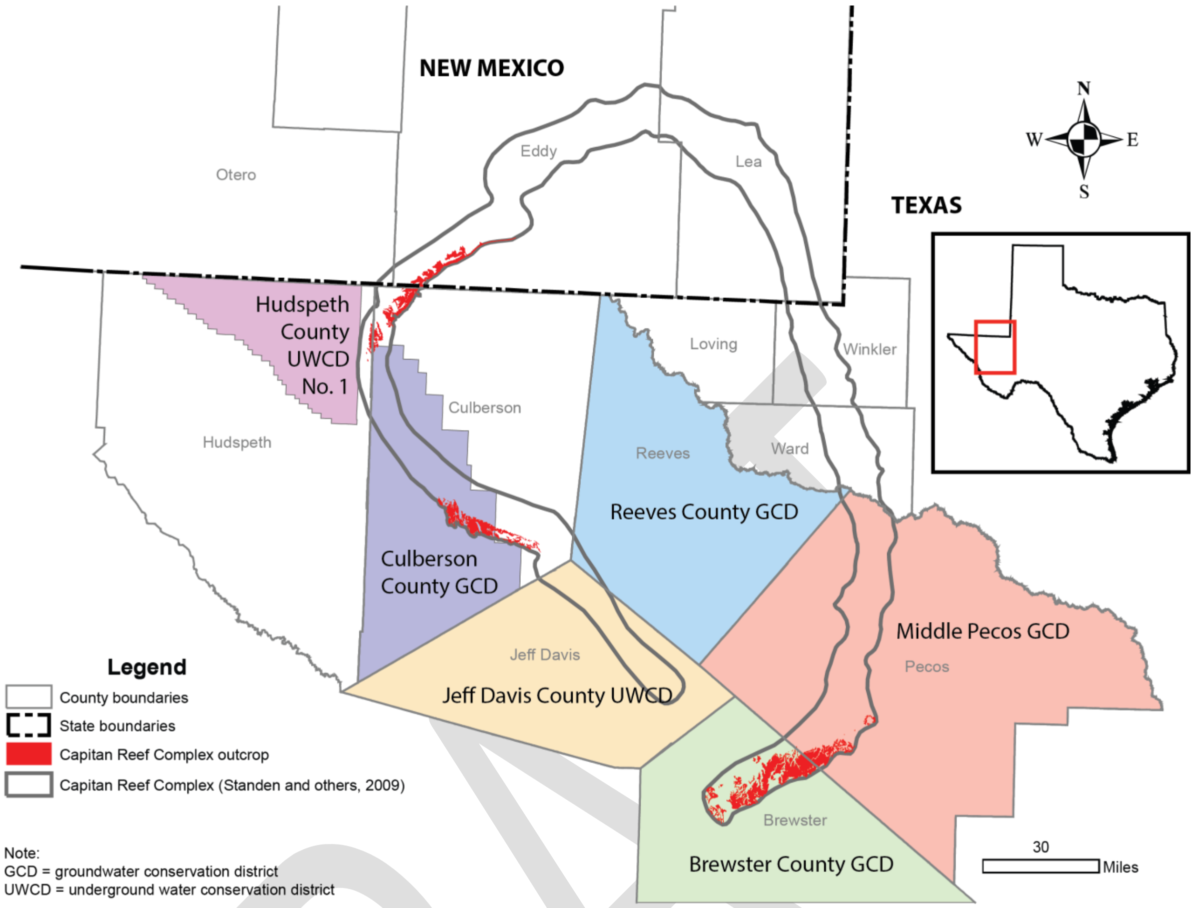


Figure 2.0.8 Texas groundwater conservation districts in the study area as of February 2014.

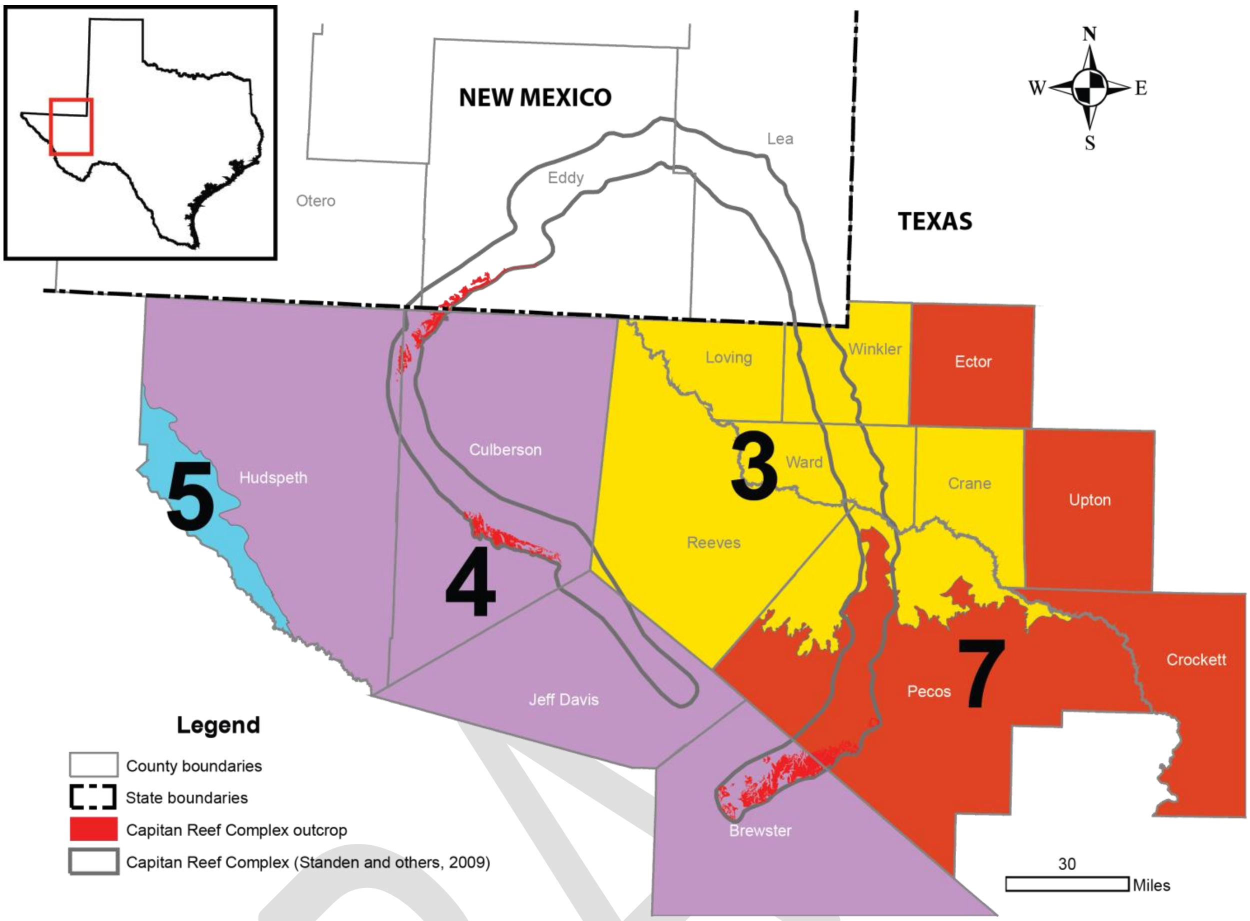


Figure 2.0.9 Texas groundwater management areas in the study area.

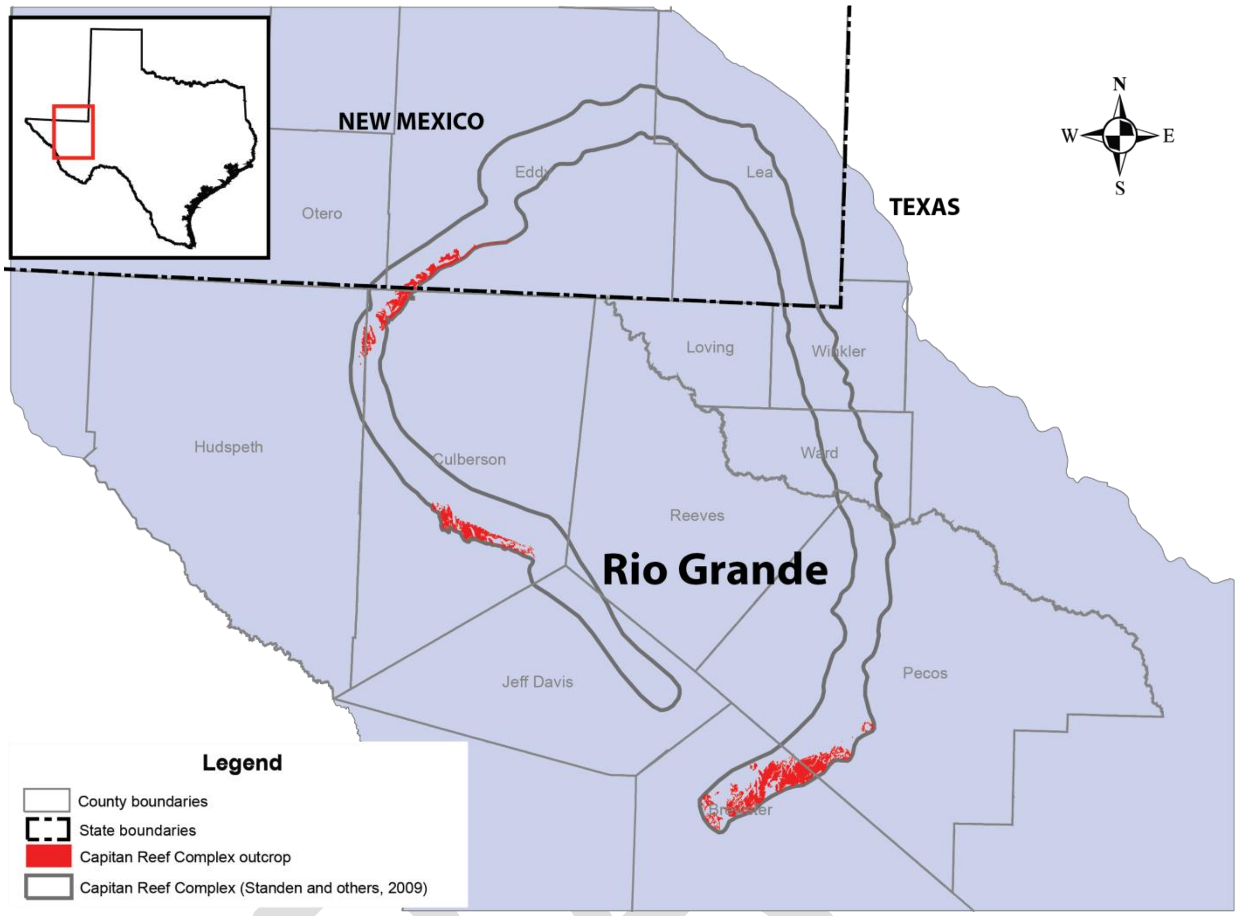


Figure 2.0.10 Major river basins in the study area.

2.1 Physiography and Climate

The study area includes parts of the Great Plains and Basin and Range physiographic provinces. In the study area, the Great Plains physiographic province consists of the Pecos Valley, Edwards Plateau, and High Plains sections, while the Basin and Range province consists of the Mexican Highland and Sacramento sections (United States Geological Survey, 2002) (Figure 2.1.1). The Pecos Valley section is a long trough lying between the High Plains on the east and the Basin and Range on the west. Its topography varies from flat plains to rocky canyon lands. This section consists chiefly of the valley of the Pecos River. The Edwards Plateau also includes the Stockton Plateau located west of the Pecos River. The two parts of the Edwards Plateau are separated by the canyon of the Pecos River. The Stockton Plateau terminates against the mountains of the Mexican Highland to the west. The High Plains are remnants of a former fluvial plain that stretched from the Rocky Mountain physiographic province located to the west. It is composed mostly of silt and sand with smaller quantities of gravel deposited by streams flowing eastward from the Rocky Mountains producing an extremely flat plain. The thickness of the unconsolidated material varies up to more than 500 feet (Leighty & Associates, Inc., 2001). Wermund (1996) describes the Basin and Range province in the study area as mountains peaks that rise abruptly from barren rock plains flanked by plateaus with nearly horizontal rocks less deformed than the adjacent mountains. The Mexican Highland is a section of the Basin and Range province that mostly occurs in Mexico but also extends along the Rio Grande. The Sacramento Section, located north of the Mexican Highland is characterized by tilted plateaus (Leighty & Associates, Inc., 2001).

The Capitan Reef Complex Aquifer is located predominantly in the Chihuahuan Deserts Level III ecological region (Figure 2.1.2). However, parts of the aquifer also underlie the Arizona/New Mexico Mountains and High Plains ecological regions. The Chihuahuan Deserts region consists of desert grassland, desert scrub in the lowlands and low mountains and wooded vegetation in the higher mountains (United States Environmental Protection Agency, 2011a). A wide variety of plant and animal life can be found in this region. Texas Parks and Wildlife Department (2012) states that *"more rare and endemic species can be found in this region than in any other part of Texas"*. The Capitan Reef Complex Aquifer crops out in the Guadalupe Mountains which is part of the Arizona/New Mexico Mountains region. The Arizona/New Mexico Mountains region has a variety of climates, depending on latitude and elevation, ranging from severe alpine climates to mid-latitude steppe and desert climates. In general, the region is marked by warm to hot summers and mild winters. Many intermittent streams and some perennial streams—both characterized by moderate to high gradients—occur in this ecological region (United States Environmental Protection Agency, 2011a). The High Plains region has a dry mid-latitude steppe climate. Historically, the High Plains region had mostly short and midgrass prairie vegetation. In the study area, the High Plains region has few to no streams. Surface water occurs in numerous playas that act as recharge areas for underlying aquifers (United States Environmental Protection Agency, 2011a).

Figure 2.1.3 provides a topographic map of the study area (Gesch and others, 2002). Land-surface elevation is greatest along an axis formed by a northwest-southeast oriented line of mountains—the Guadalupe, Delaware, Apache, Jeff Davis, Barilla, and Glass mountains—and generally decreases to the east and west to the Pecos River Valley and Salt Basin, respectively. Land-surface elevation in the footprint of the Capitan Reef Complex Aquifer varies from over 8,000 feet above mean sea level in the Guadalupe Mountains in Culberson and Hudspeth counties to about 2,400 feet above mean sea level at the Pecos River along the border of Ward and Pecos counties.

The climate in the study area, shown in Figure 2.1.4, is classified as Subtropical Arid over most of the Capitan Reef Complex Aquifer, Continental Steppe to the northeast, and Mountain in the Guadalupe Mountains of Hudspeth and Culberson counties and the Davis Mountains in Jeff Davis County (Larkin and Bomar, 1983). The Subtropical Arid climate is the result of decreasing moisture content of air flowing inland from the Gulf of Mexico (Larkin and Bomar, 1983). This climate region is characterized by anomalous summertime rainfall associated with mountains. The Continental Steppe climate is the typical climate of the High Plains. It is a semi-arid climate characterized by large variations in daily temperatures, low relative humidity, and irregularly spaced moderate rainfall (Larkin and Bomar, 1983). The Mountain climate is characterized by cooler temperatures, lower relative humidity, and mountainous precipitation anomalies typical of areas with orographic precipitation controls. This climate is associated with the highest mountain ranges in the region—the Davis and Guadalupe mountains—which include the highest mountain peaks in Texas (Larkin and Bomar, 1983). The average annual maximum air temperature in the study area ranges from a high of about 58 degrees Fahrenheit in the Pecos River Valley to a low of about 46 degrees Fahrenheit in the Guadalupe Mountains (Figure 2.1.5).

Figure 2.1.6 shows average annual precipitation for the period 1971 through 2000 (Oregon State University, 2006a). The highest annual precipitation of about 28 inches per year occurs in the Guadalupe Mountains in Culberson County and the lowest annual precipitation of less than 10 inches per year occurs in an adjacent part of the Salt Basin along the Culberson-Hudspeth county boundary.

Precipitation data are available at twenty three Texas and eighteen New Mexico stations within the study area (Figure 2.1.7). In general, measurements are not continuous on a month by month or year by year basis for the gages. Annual precipitation recorded at eight stations in the study area is shown in Figure 2.1.8. Figure 2.1.8 indicates wide interannual variation of precipitation, ranging from lows of about 5 inches to more than 25 inches per year. Figure 2.1.9 shows long-term average monthly variation in precipitation at eight gages in the study area. In the study area, monthly precipitation is generally highest during summer and early fall months—May through October.

The average annual net pan evaporation rate in the study area ranges from a high of 72 inches per year to a low of 55 inches per year and averages about 64 inches per year (Figure 2.1.10; TWDB 2012a). Average annual net pan evaporation is generally lowest in the southern part of the study area, increasing to the north and east. Pan evaporation rates significantly exceed the annual average precipitation. Monthly variations in lake surface evaporation are shown in for seven locations in the study area (Figure 2.1.11; TWDB, 2012a). These values represent the average of the monthly lake surface evaporation data from January 1954 through December 2011. Figure 2.1.11 shows that average lake evaporation peaks in June or July.

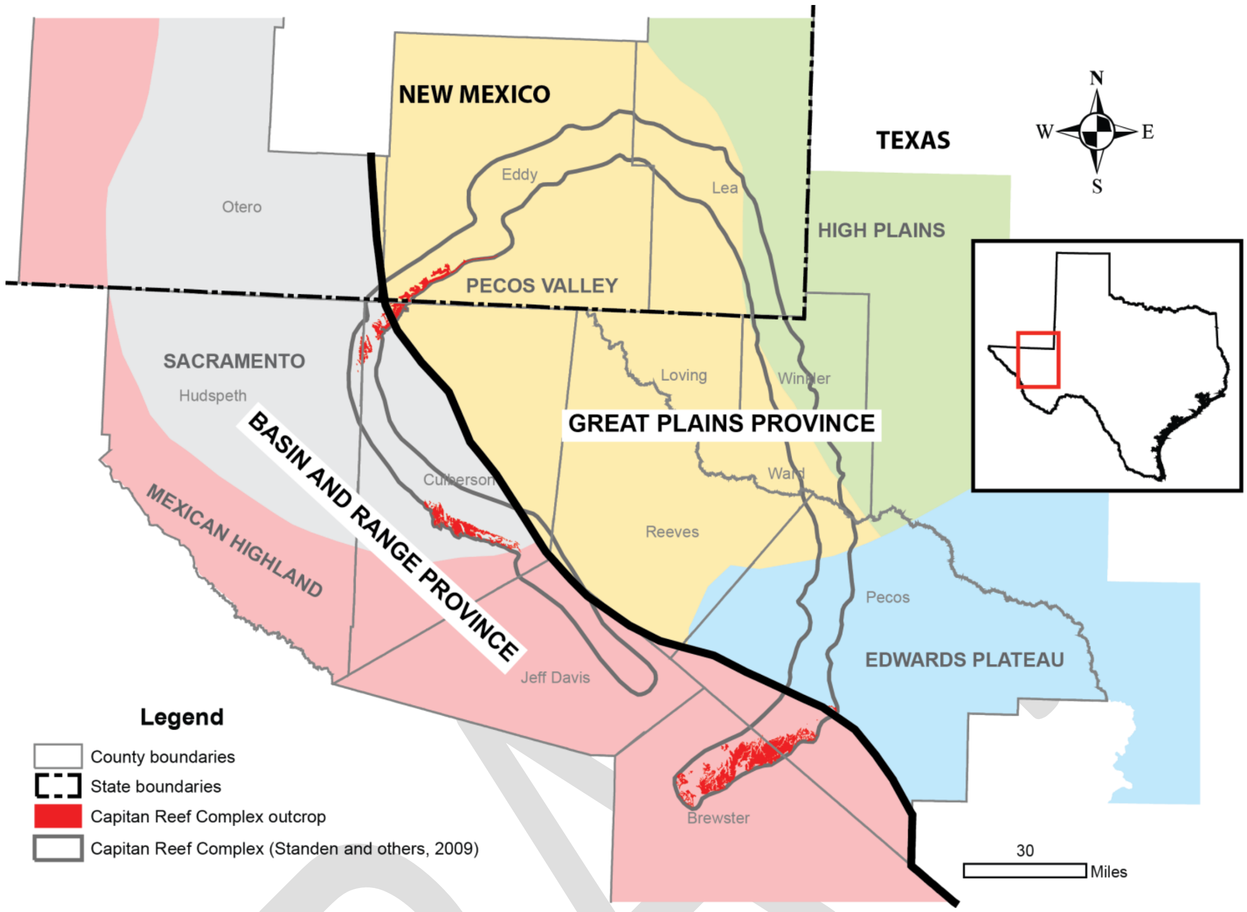


Figure 2.1.1 Physiographic provinces in the study area (United States Geological Survey, 2002).

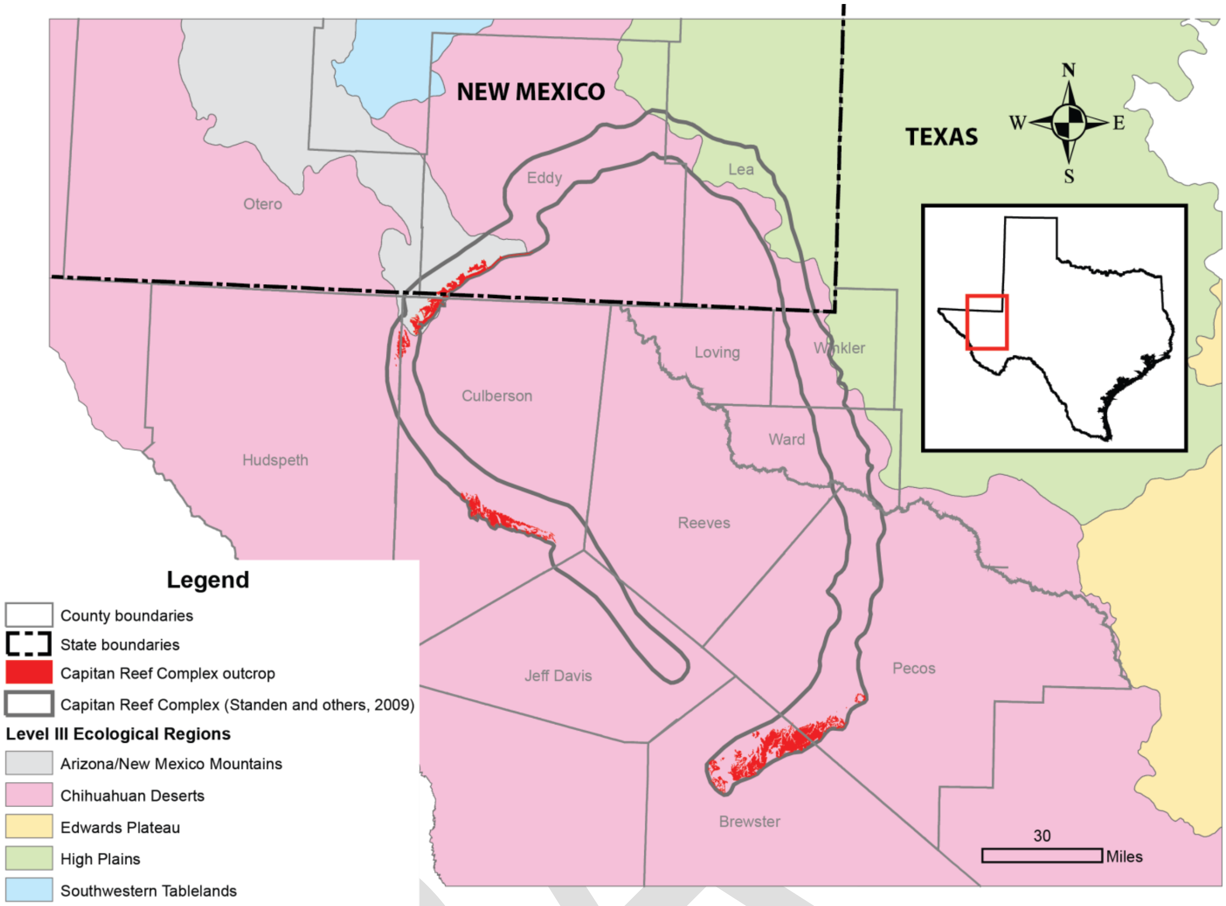


Figure 2.1.2 Level III ecological regions in the study area (United States Environmental Protection Agency, 2011b).

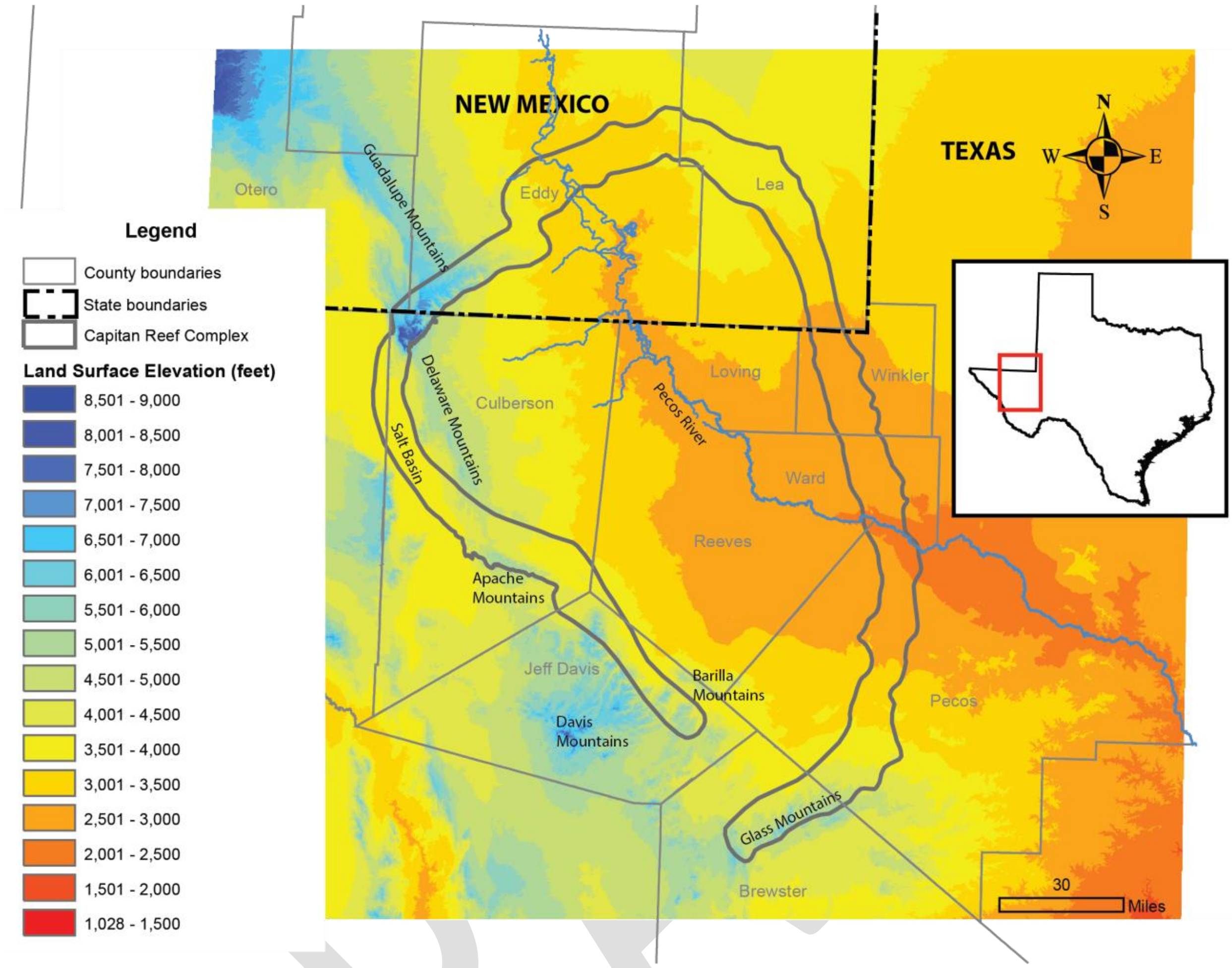


Figure 2.1.3 Topographic map of the study area showing land surface elevation in feet above mean sea level. Based on data from Gesch and others (2002).

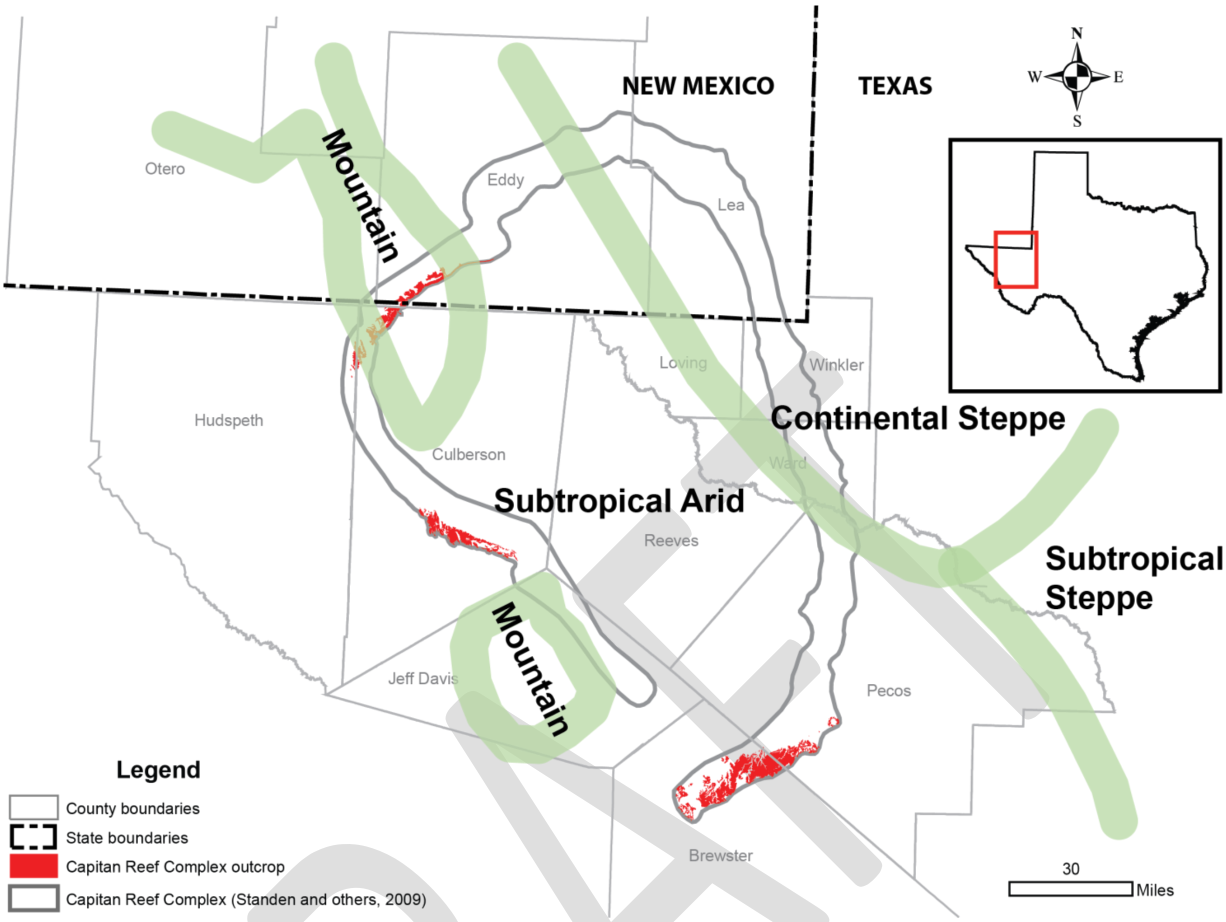


Figure 2.1.4 Climate classifications in the study area (modified from Larkin and Bomar, 1983).

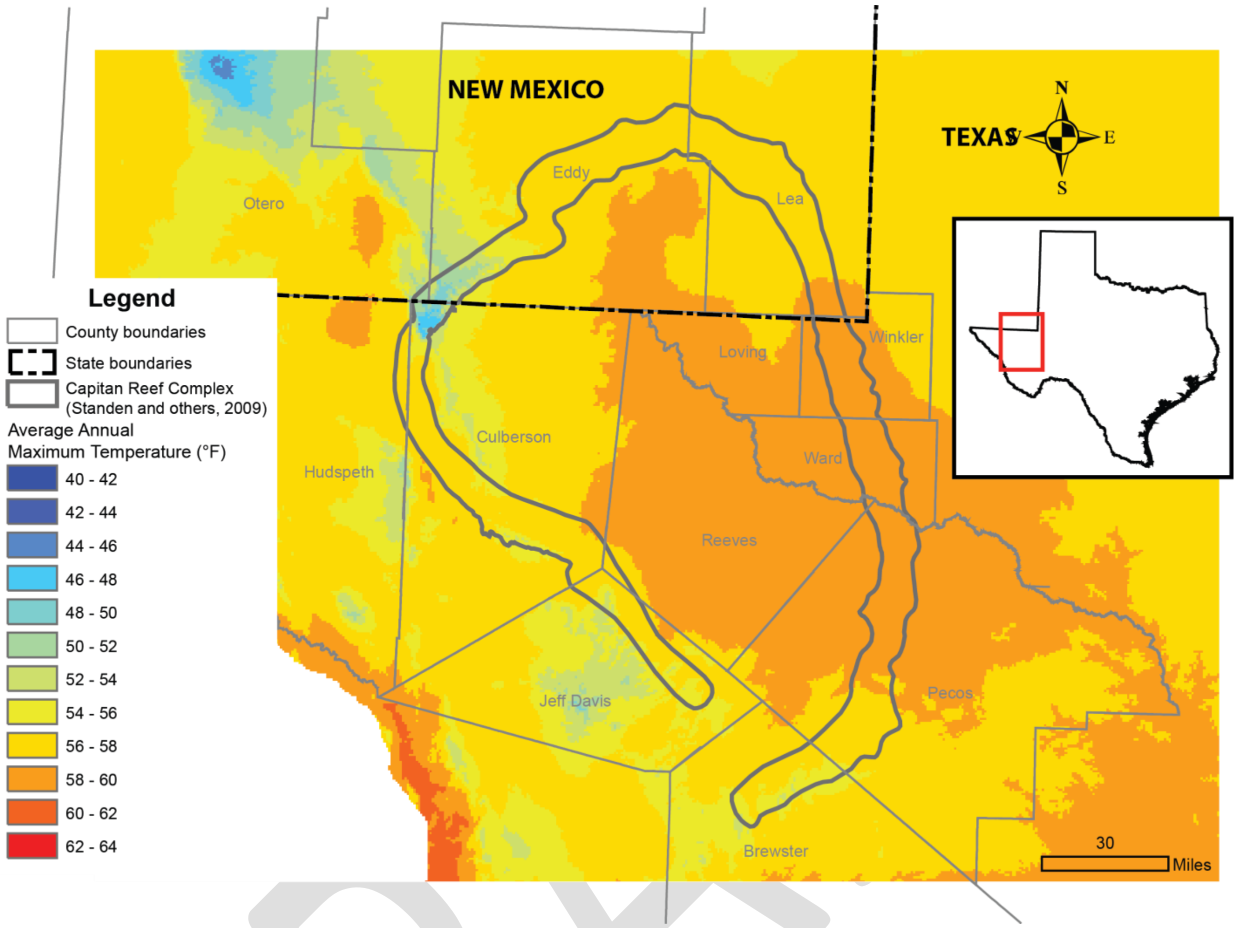


Figure 2.1.5 Average annual air temperature in degrees Fahrenheit in the study area. Based on 1971 to 2000 PRISM data (Oregon State University, 2006b).

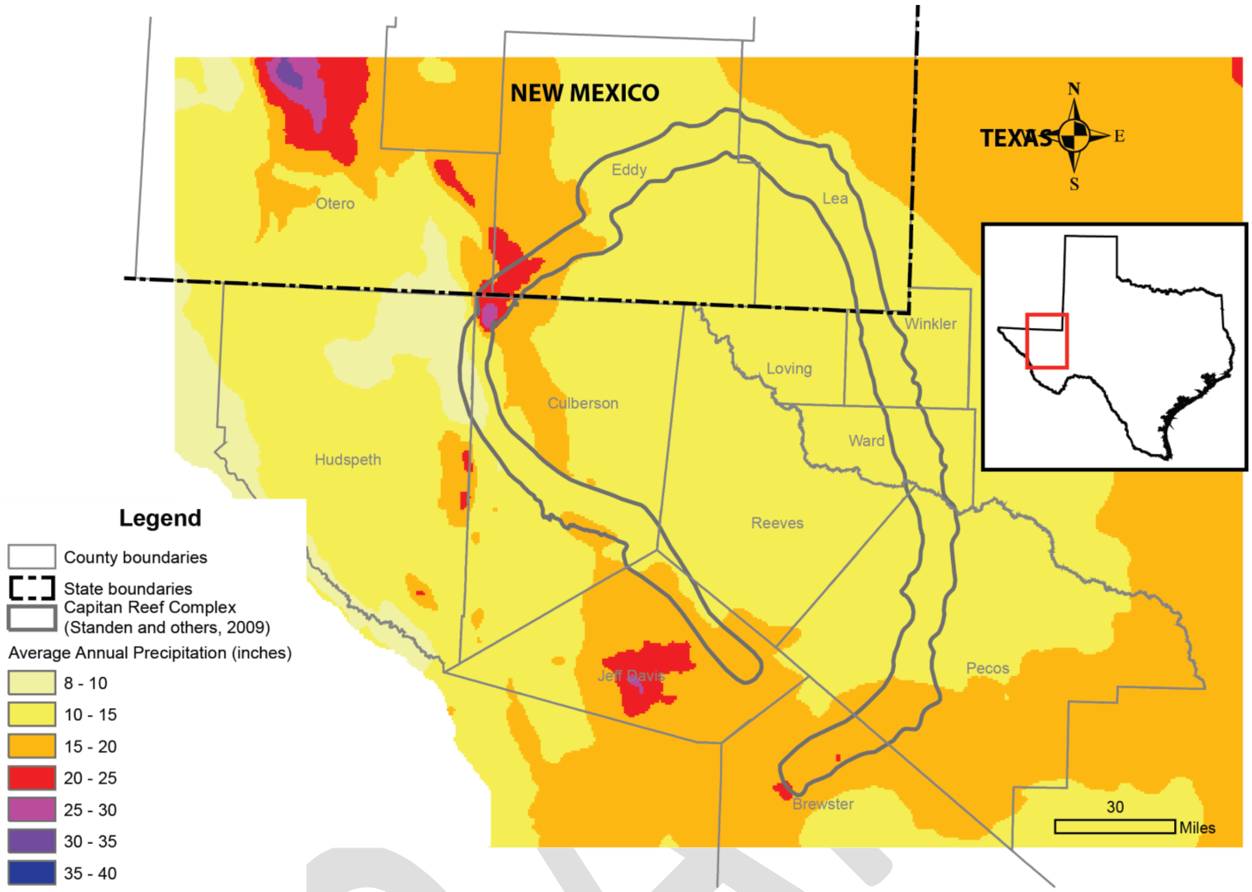


Figure 2.1.6 Average annual precipitation in inches per year in the study area for the time period 1971 through 2000 (Oregon State University, 2006a).

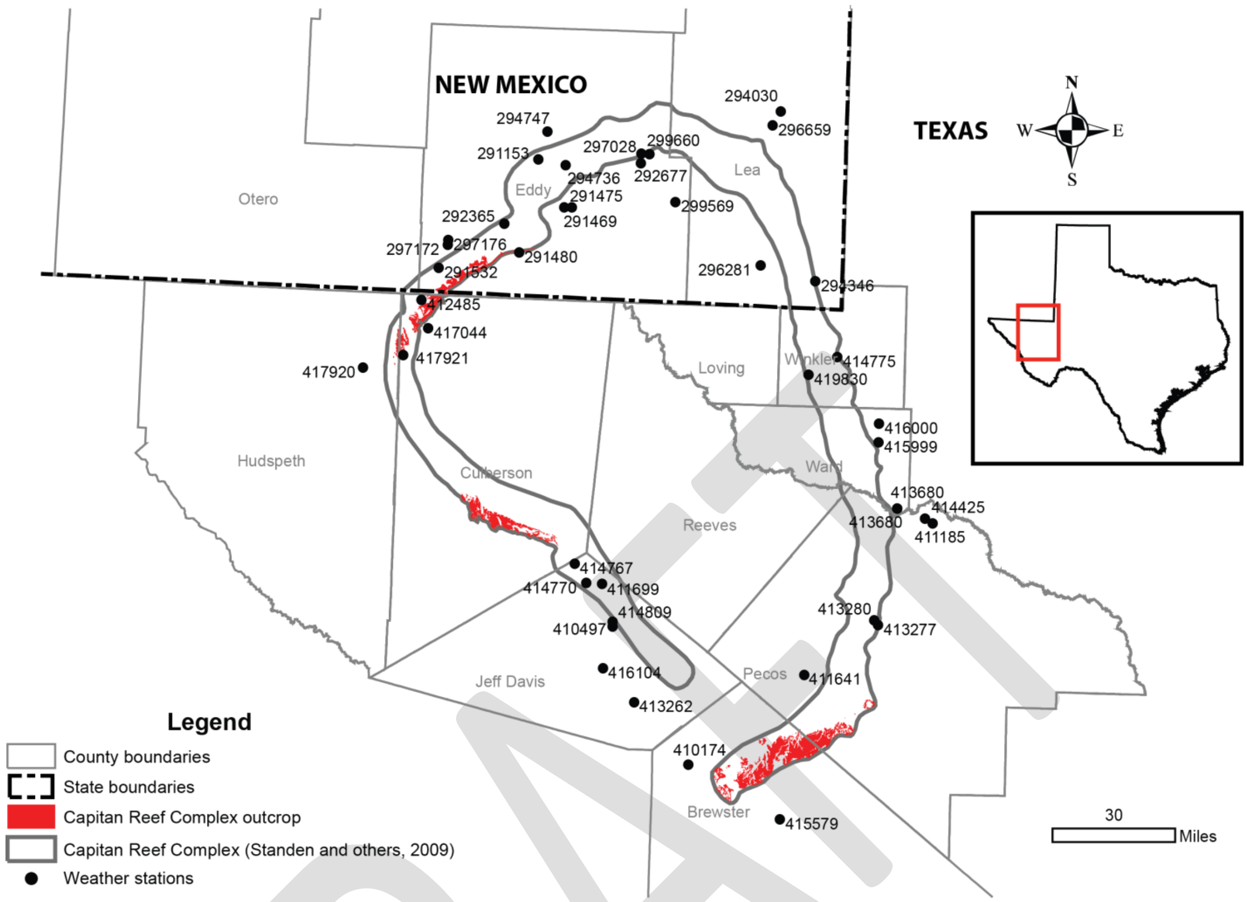


Figure 2.1.7 Location of precipitation gages in the study area (National Climatic Data Center, 2011).

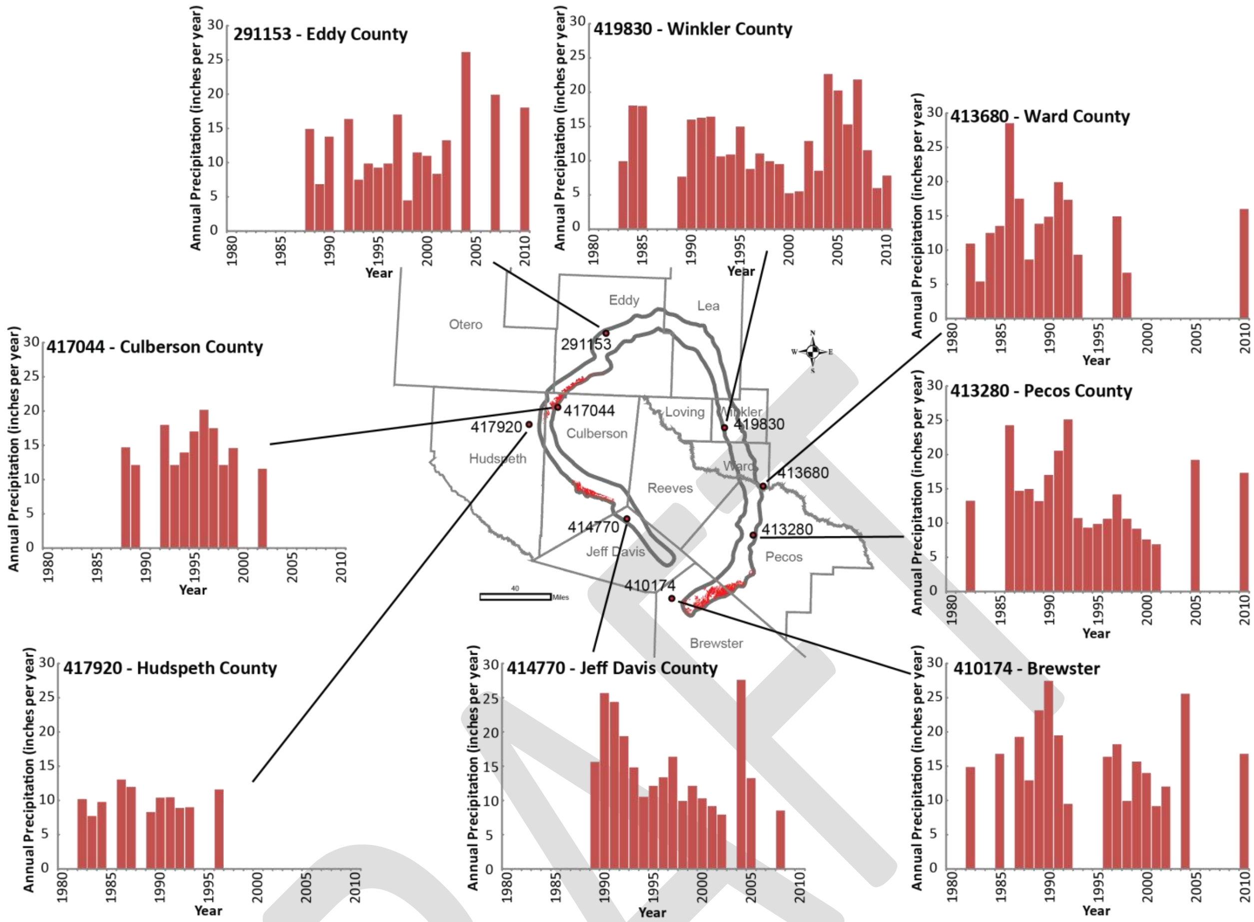


Figure 2.1.8 Selected time series of annual precipitation in inches per year in the study area (National Climatic Data Center, 2011). Zero values indicate missing data.

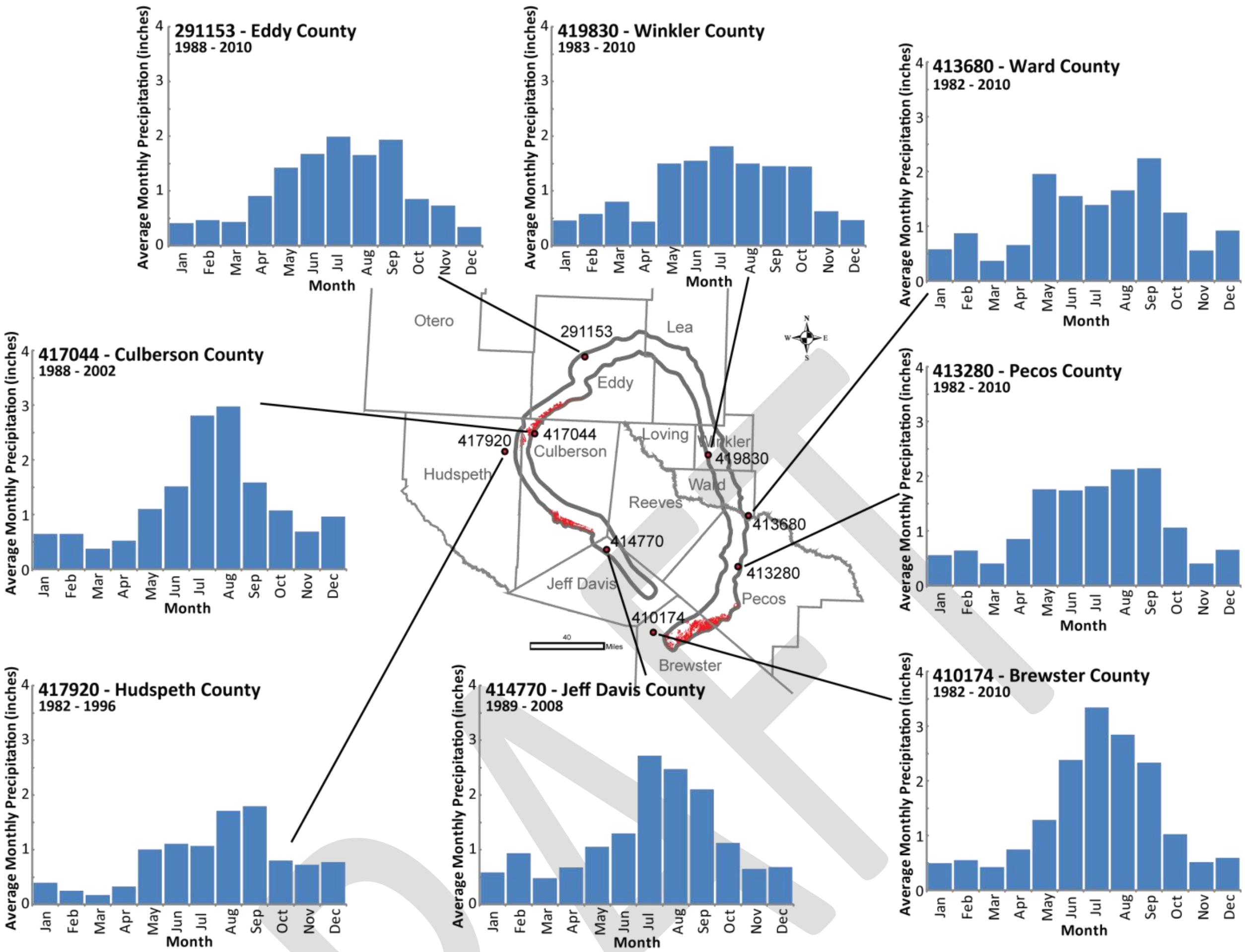


Figure 2.1.9 Selected time series of average monthly precipitation in inches per month in the study area (National Climatic Data Center, 2011).

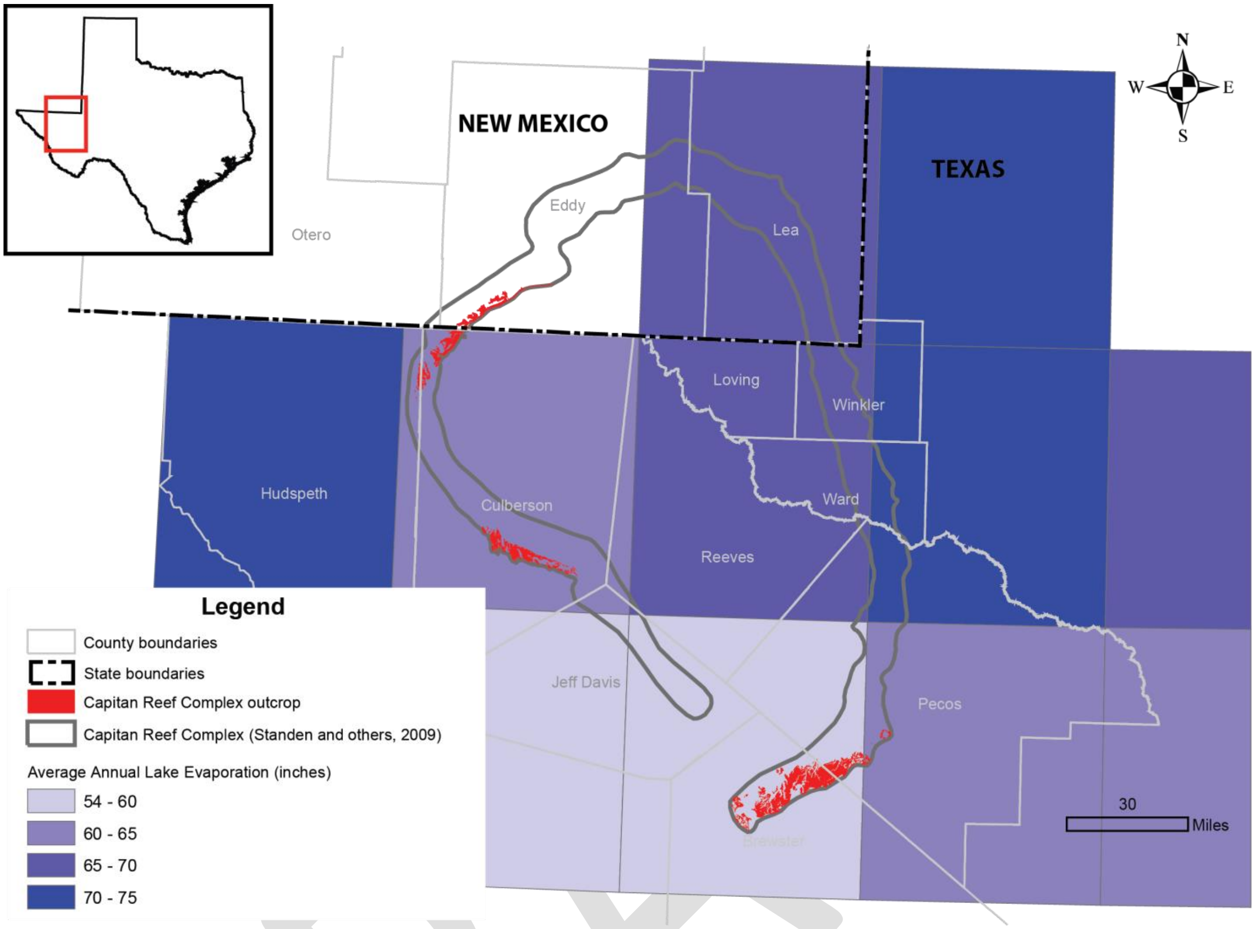


Figure 2.1.10 Average annual net pan evaporation rate in inches per year over the Texas portion of the study area (Texas Water Development Board, 2012a).

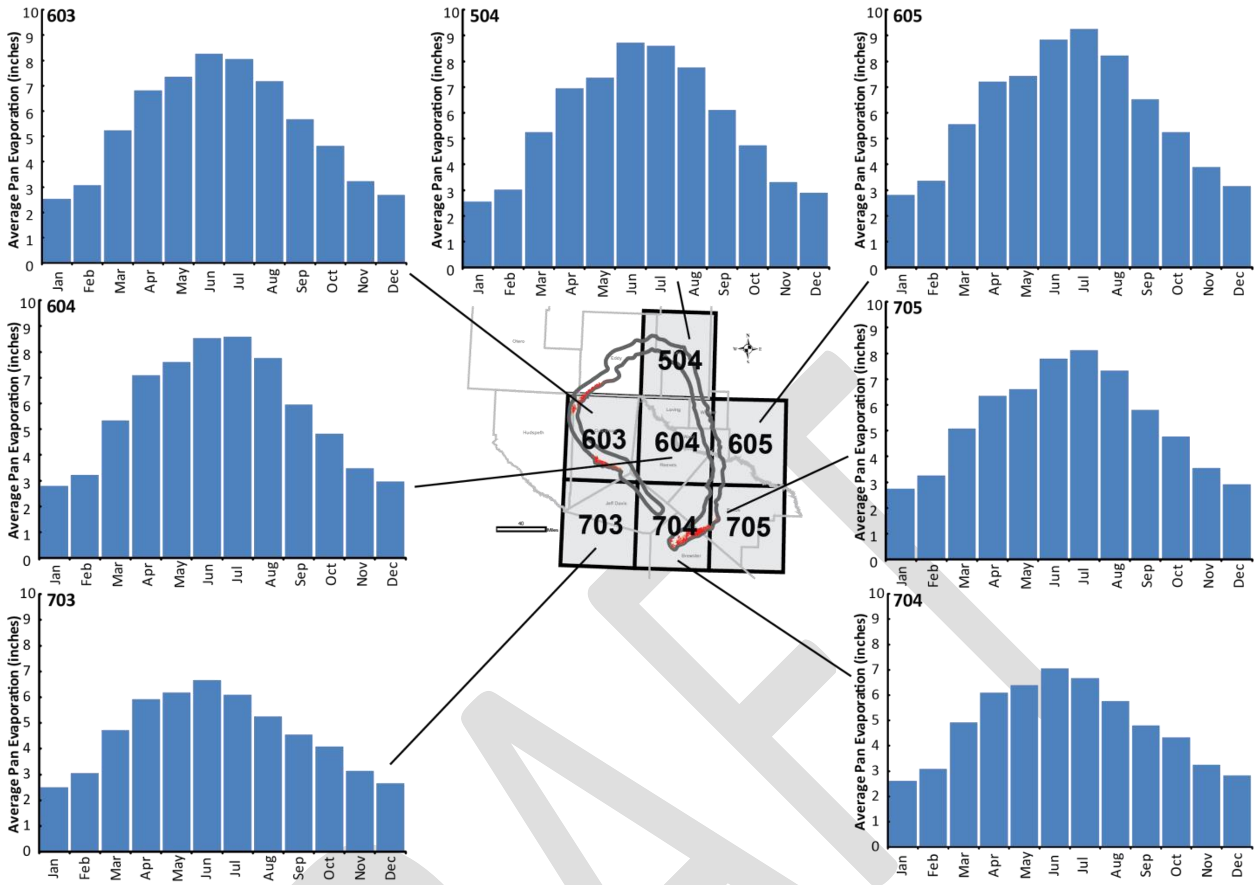


Figure 2.1.11 Average monthly lake surface evaporation in inches in selected map quadrangles in the study area (Texas Water Development Board, 2012a).

2.2 Geology

This section provides a brief discussion of the geology of the study area. The discussion is divided into the structural setting, the surface geology, and the stratigraphy of the Capitan Reef Complex, including a description of geologic structural cross-sections through the study area.

2.2.1 Structural Setting

The structural setting for the study area is shown in Figure 2.2.1 (after Armstrong and McMillion, 1961). The primary structural features within the study area include the Delaware Basin, Central Basin Platform, Diablo Platform, Northwestern Shelf, Hovey Channel, and Sheffield Channel. The Capitan Reef Complex occurs along the margins of the Delaware Basin. This basin is surrounded by structural highs—the Northwest Shelf to the north, the Central Basin Platform to the east, the Diablo Platform to the west, and the Southern Shelf and Marathon Folded Belt to the south. The Delaware Basin is also connected to adjacent basins by the Hovey and Sheffield channels that connect the Delaware Basin to the Marfa and Midland basins, respectively.

2.2.2 Surface Geology

Figure 2.2.2 is a geologic map of the study area. Over the majority of the study area, the predominant surficial deposits are Quaternary-age alluvial and eolian sediments. Permian and Cretaceous outcrops occur in the northwestern and southeastern parts of the study area, mostly associated with mountains, such as the Guadalupe, Delaware, Apache, and Glass mountains. The major outcrops of the Capitan Reef Complex occur in the Guadalupe, Apache, and Glass mountains.

2.2.3 Capitan Reef Complex and Delaware Basin Stratigraphy

The Capitan Reef Complex forms a horseshoe-shaped feature along the margins of the Permian Delaware Basin and consists of massive fossiliferous white limestone (Figure 2.2.1). The Capitan Reef Complex combines the Goat Seep Dolomite, Capitan Limestone, Carlsbad Limestone, and the Tessey and Vidrio formations (Hiss, 1975) and grades into adjacent fore-reef and back-reef facies (Figure 2.2.3). The Capitan Reef Complex geologic model of fore-reef, reef, and back-reef facies was described in detail by King (1948) and by Melim and Scholle (1999).

The back-reef or shelf facies occur behind the reef complex. These facies are characterized by quartz sandstone and siltstone with carbonate and evaporite facies, and consist of the Artesia Group— the Grayburg, Queen, Seven Rivers, Yates, and Tansill formations (Figure 2.2.4). The Queen, Grayburg, and Yates formations contain more sandstone beds than the Seven Rivers and Tansill formations (Motts, 1968). Carbonate facies occurs adjacent to the Capitan Reef Complex while the evaporite facies occurs farther away. The boundary between the evaporite and carbonate facies shifts closer to the shelf margin in the younger formations of the Artesia Group from 15 to 20 miles from the shelf margin in the Queen Formation to about 5 to 10 miles in the Tansill Formation.

The fore-reef or basin facies consist of the Castile Formation and the Delaware Mountain Group. The Delaware Mountain Group is 2,700 to 3,500 feet thick and consists of the Brushy Canyon, Cherry Canyon, and Bell Canyon formations (Motts, 1968). The formations of the Delaware Mountain Group are predominantly sandstone with carbonate beds occurring in the Cherry Canyon and Bell Canyon formations. The Castile Formation consists of evaporites and thin beds of limestone, shale, and sandstone.

The Capitan Reef Complex is exposed in outcrops in the Guadalupe Mountains (Eddy County, New Mexico and Culberson County, Texas), Patterson Hills (Culberson and Hudspeth counties, Texas), Apache Mountains (Culberson and Jeff Davis counties, Texas), and Glass Mountains (Brewster and Pecos counties, Texas) (Figure 2.2.2). Geologic descriptions stem primarily from detailed mapping in the Guadalupe and Glass Mountains (King, 1930, 1948). Figures 2.2.5 through 2.2.7 show three representative cross-sections through the eastern arm of the Capitan Reef Complex. Figures 2.2.5 and 2.2.6 show east-west oriented cross-sections through the Capitan Reef Complex in Lea County, New Mexico and Pecos County, Texas, respectively, where the Capitan Reef Complex occurs in the subsurface. Figure 2.2.7 is a northwest-southeast oriented cross-section through the Capitan Reef Complex outcrop in the Glass Mountains of Brewster County, Texas. In this area, the Capitan Reef Complex dips towards the northwest, is overlain by Cretaceous sediments, and is cross-cut by faults and Tertiary igneous intrusions.

Deposition of the Capitan Reef Complex occurred around the margin of the Delaware Basin and on the edge of the northwestern shelf. Surface outcrops and subsurface expression of the Capitan Reef Complex in the Guadalupe, Apache, and Glass mountains are shown on Figure 2.2.2. The arc-shaped reef structure is about 10 to 14 miles wide and is dissected by the Hovey Channel in Brewster County (Hill, 1996; Hiss, 1975). There is also some evidence suggesting another channel located in the western part of the Capitan Reef Complex (Hill, 1999; 2006).

The Capitan Reef Complex is composed of massive white to gray fossiliferous limestone beds. The limestone beds grade from fore-reef to back-reef deposits. The gradation into fore-reef deposits is typically abrupt, with a defined geologic contact, whereas the gradation into back-reef deposits is more transitional, with difficult-to-identify geologic contacts (Hill, 1996; Hiss, 1975).

The rocks that make up the reef complex have been locally dissected by faults and consequently do not form one continuous aquifer but rather a series of disconnected highly permeable aquifers (Hill, 1996; Hiss, 1975) (Figure 2.2.8). For example, the uplifted Guadalupe Mountains divide the Capitan Reef Complex Aquifer into two separate disconnected aquifers, one that trends to the northeast and discharges to the Pecos River in New Mexico and one that originates along the western flank of the Guadalupe Mountains and flows south toward the Apache Mountains (Hiss, 1975; King, 1948).

The Delaware Basin—around which the Capitan Reef Complex formed—was a foreland basin formed when the Ouachita Mountains—located south and east of the study area—were uplifted as the southern supercontinent Gondwana collided with the supercontinent Laurasia during the Pennsylvanian period. This basin formed by subsidence that took place through the early and middle Permian—Leonardian and Guadalupian epochs. Rapid subsidence of the basin started in the middle Guadalupian Epoch of the upper Permian. Patch reefs responded by rapid (mostly vertical) growth, resulting in the deposition of the Goat Seep Dolomite reefs (Harris and others, 1997). The Capitan Reef Complex was built primarily from calcareous sponges and encrusting algae such as stromatolites and directly from seawater as a limey mud (Harris and others, 1997).

Sea level dropped as sedimentation continued to infill the Delaware Basin into the Ochoan epoch of the upper Permian, periodically cutting the basin off from its source of seawater. Part of the resulting brine became the deep-water evaporites of the overlying Castile and Salado formations (Harris and others, 1997). The Rustler Formation evaporites and dolomite represent the uppermost occurrence of evaporites in the Delaware Basin as the basin as final in-filling and buried beneath non-marine sediments took place (Holt and Powers, 1990a, 1990b, 2011).

The Delaware Basin was filled at least to the top of Capitan Reef Complex and was mostly covered by dry land before the end of the Ochoan epoch. Rivers migrated over its surface and deposited the red silt and sand that now constitute the siltstone and sandstone of the Dewey Lake Formation and Dockum Group (McGowen and others, 1979; Harris and others, 1997). A karst topography developed as groundwater circulated in the buried limestone formations, dissolving away the rock to form voids and underground caverns, which were later destroyed by infill and erosion (Harris and others, 1997). Uplift associated with the Laramide Orogeny in the late Mesozoic and early Cenozoic ages created a major fault along which the Guadalupe Mountains were thrust into existence. The mountain range forms the tilted up-thrown part of the system and the Salt Flat Bolson forms the downfallen block (Figure 2.2.8). The Capitan Reef Complex was exposed above the surface, with the 8,000-foot-high El Capitan its most prominent feature. Other large outcrops compose the Apache Mountains and Glass Mountains to the south (Harris and others, 1997).

The Guadalupe Mountains high coincides with the up-thrown—eastern—side of the Border Fault Zone (Figure 2.2.8). The Apache Mountains—another structural high in the Capitan Reef Complex—coincides with the up-thrown side of the Stocks Fault. The relatively low area between the Border Fault Zone and the Stock Fault is a graben that forms part of the Salt Basin.

During the Late Cretaceous and Early Tertiary periods, the study area was uplifted and tilted slightly to the east. Subsequently, Late Tertiary Basin and Range block faulting formed the Guadalupe, Delaware, Apache, and Glass mountains and Patterson Hills. Major displacements of the Capitan Reef Complex by faulting are limited to the mountainous areas along the western and southern margins of the Delaware Basin (Figure 2.2.8). In addition to faults, the Capitan Reef Complex Aquifer has fissures parallel and perpendicular to the reef face.

Faults, fractures, and fissures play a very important role in local and regional groundwater flow patterns within the Capitan Reef Complex Aquifer. Tectonic events that occurred during the past billion years—Ouachita orogeny, Laramide orogeny, and Basin and Range extension—have resulted in fracture patterns that control groundwater flow paths (Uliana, 2000). Subsequent karstification of these fractures within the Capitan Reef Complex and overlying Cretaceous carbonates has produced highly permeable pathways for groundwater flow. Areas with large fault offsets may result in the stratigraphic alignment of more permeable Capitan Reef Complex carbonates with adjacent less permeable subsurface formations, such as the Delaware Mountain Group or Artesia Group. This juxtaposition of subsurface formations may significantly impact local and regional groundwater flow systems. Even in the absence of faulting, the Capitan Reef Complex Aquifer is surrounded both vertically and laterally by less permeable fore-reef and back-reef stratigraphic units that have the potential to restrict groundwater flow into and out of Capitan Reef Complex Aquifer (White, 1971; Standen and others, 2009).

Streams eroded away the softer sediment, lowering the ground level to its current position. Submarine canyons are incised in the Capitan Reef Complex along the northern and eastern margins of the Delaware Basin. Hiss (1975) identified 25 submarine canyons where the top of the Capitan Reef Complex is structurally low. These submarine canyons were eventually filled with low permeability material. Hiss (1975) believes that these submarine canyons restrict groundwater flow through the reef carbonates. Acidic groundwater excavated caves in the limestone of the higher areas, and eroded sediment helped fill any remaining Permian-aged caves. Unlike most other caves that are formed in limestone, the source of acidity that formed these caves was likely hydrogen sulfide and sulfide-rich brines freed by tectonic activity during the mid-Tertiary age. These acidic brines mixed with oxygenated groundwater, forming sulfuric acid. The Carlsbad Caverns and nearby modern caves started to form during this time below the water table. Additional uplift of the Guadalupe Mountains during the Pliocene and early Pleistocene epochs have enlarged Carlsbad Caverns and other nearby caves (Harris and others, 1997).

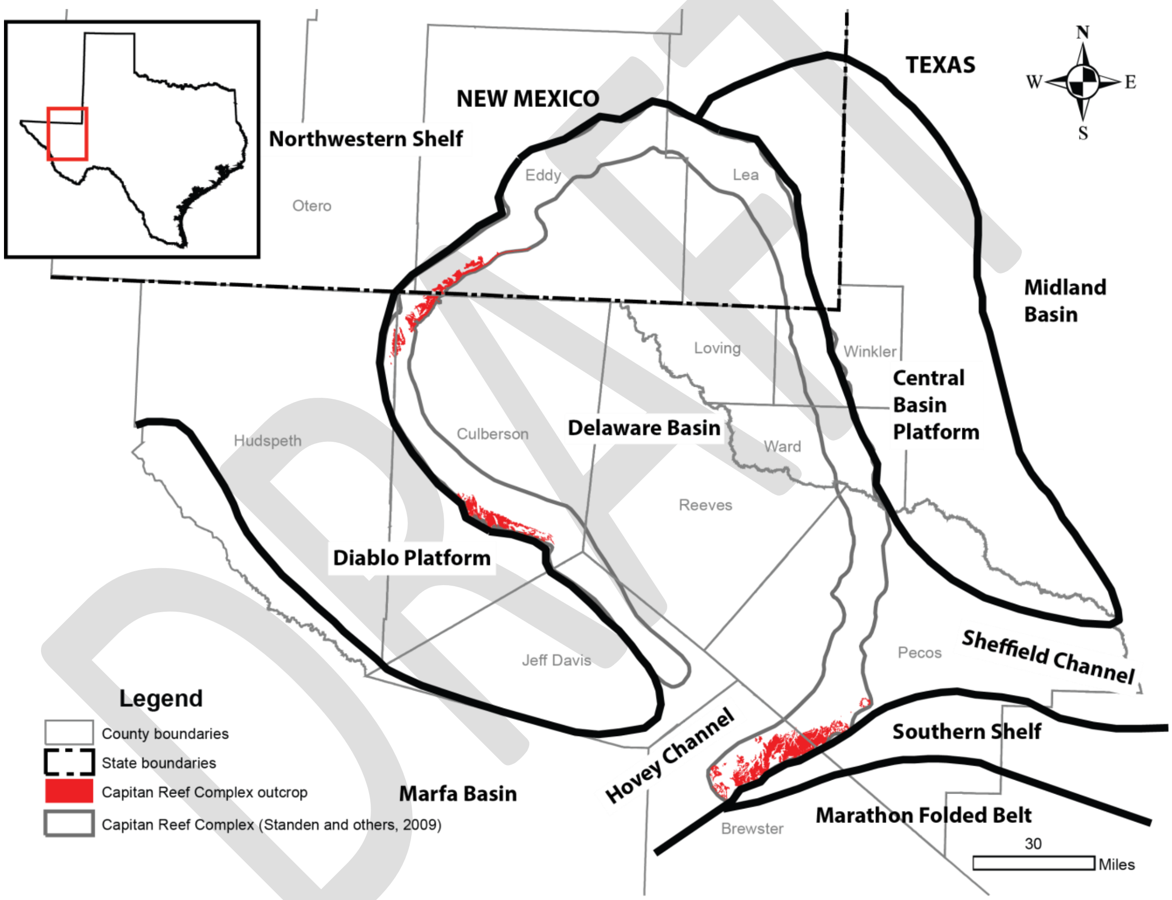


Figure 2.2.1 Major structural features in the study area (from Armstrong and McMillion, 1961).

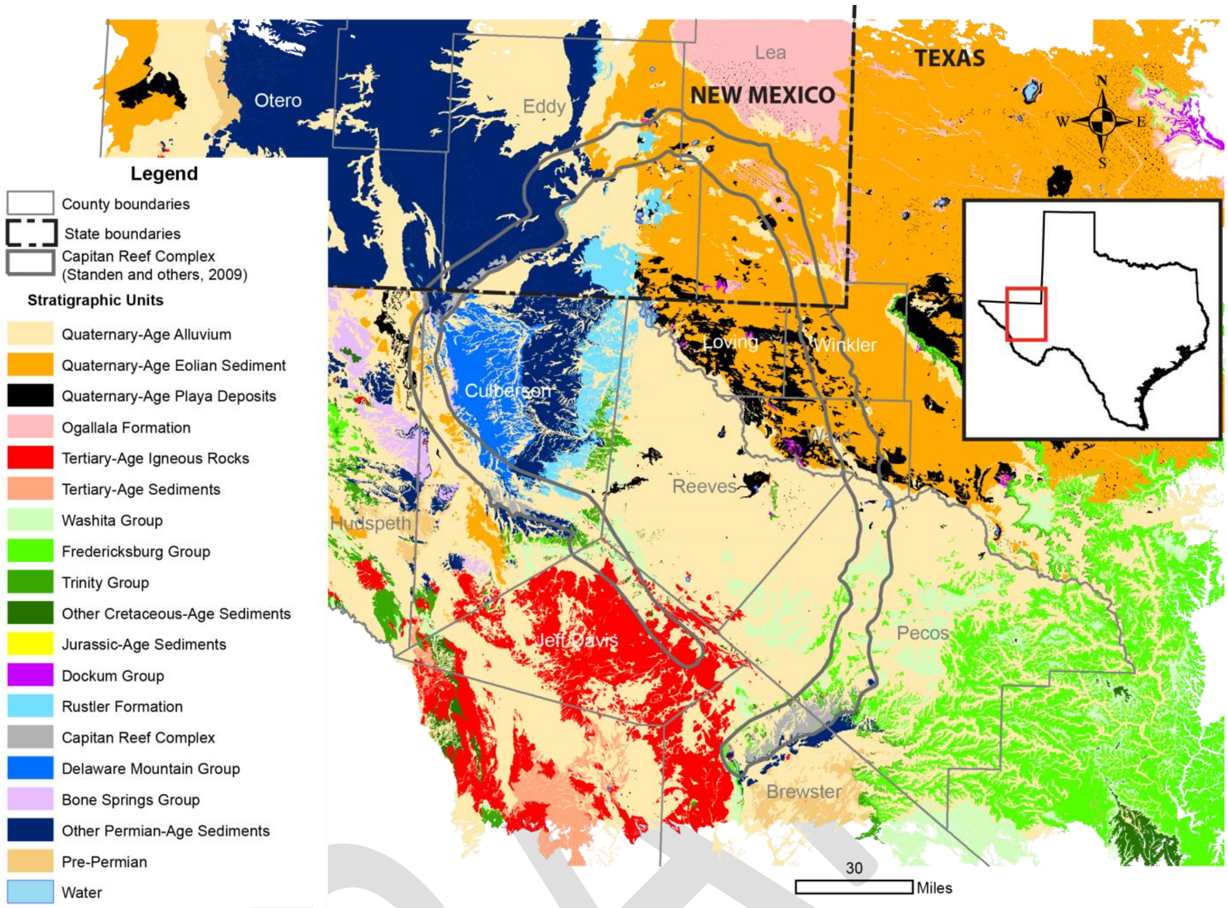


Figure 2.2.2 Generalized surface geology in the study area.

Summary of geologic formations and groups forming the Capitan Reef Complex and Delaware Basin

Period/Epoch or Series	Apache Mountains (Wood, 1968; Uliana, 2001) Back Reef	Apache Mountains Reef	Guadalupe Mountains (King, 1948; Hiss, 1975; Kerans and others, 1994; Kerans and Tinker, 1999) Back Reef	Guadalupe Mountains Reef	Glass Mountains (King, 1930; Hill, 1999) Back Reef	Glass Mountains Reef	Delaware Basin
Quaternary to Tertiary	Quaternary Tertiary Deposits		Quaternary Tertiary Deposits		Quaternary Tertiary Deposits		Pecos Valley Alluvium
Cretaceous					Cretaceous		Edwards/Trinity Groups
Triassic					Bissett		Dockum Group
Permian/Ochoan				Rustler [a] Salado [a] Castile [a]			Rustler Salado Castile
Permian/ Guadalupian	Artesia Group: Tansill	*Capitan Reef Complex*; Capitan Limestone	Artesia Group: Tansill	*Capitan Reef Complex*; Carlsbad and Capitan Limestones	Gilliam	*Capitan Reef Complex*; Tessey	Delaware Mountain Group: Bell Canyon
	Yates		Yates				
	Seven Rivers		Seven Rivers			Vidrio	Cherry Canyon
	Munn		Queen/Grayburg	Goat Seep Dolomite			
	Cherry Canyon		Upper San Andres Lower San Andres (Brushy Canyon Equivalent)	Cherry Canyon	Word Formation (Cherry and Brushy Canyon Equivalent)		Brushy Canyon
	Cutoff Shale (Member of Bone Spring Limestone)						Pipeline Shale Member
Permian/ Leonardian	Yeso	Victorio Peak (Member of the Bone Spring Limestone)			Leonard and Hess Member of Leonard Formation		Bone Spring Limestone

Sources: From Standen and others (2009): Modified after King, 1930, 1948; Wood, 1968; Hiss, 1975; Uliana, 2001; Hill, 1999; Kerans and others, 1994; Kerans and Tinker, 1999.

[a] Formations overlie Capitan Reef Complex between the Guadalupe and Glass Mountains

Figure 2.2.3 Generalized stratigraphic column for the Capitan Reef Complex and overlying and underlying formations.

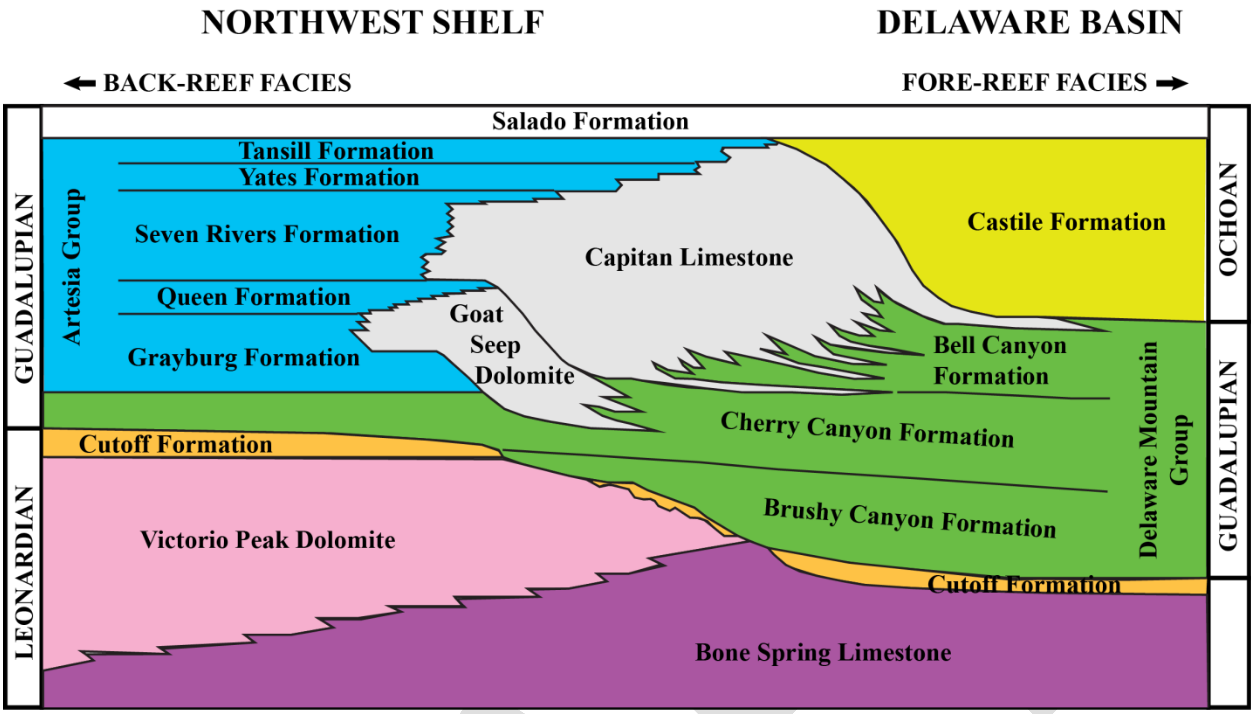
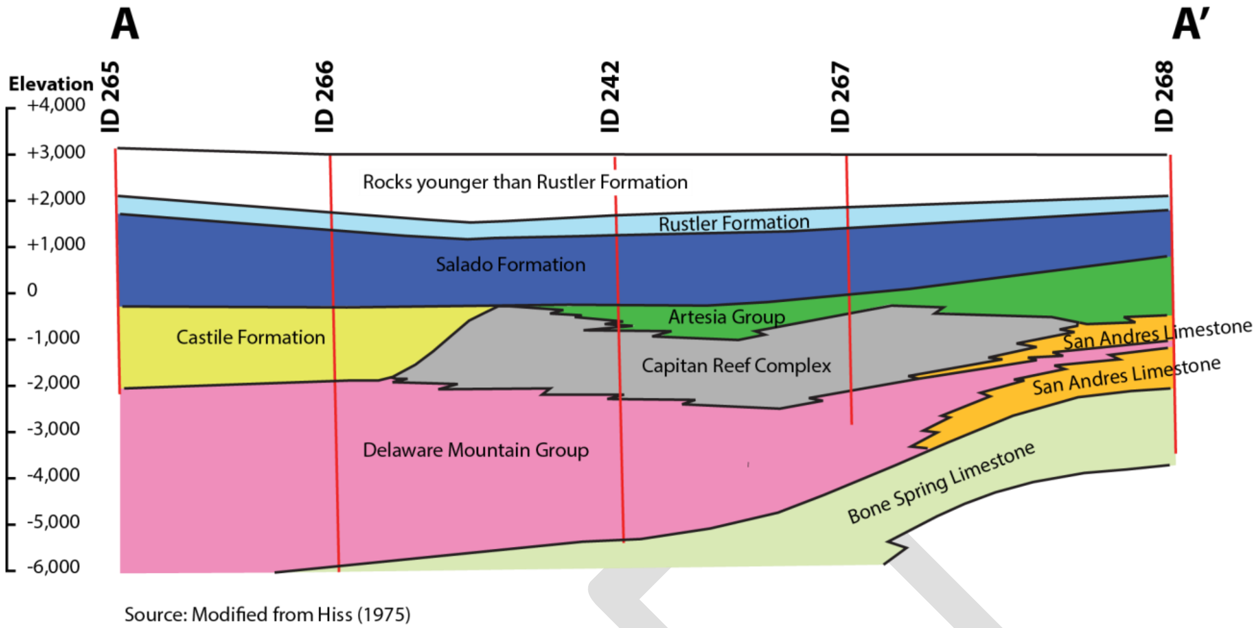


Figure 2.2.4 Generalized cross-section through the Capitan Reef Complex and associated fore-reef and back-reef facies formations. Modified from Standen and others, 2009; Melim and Scholle, 1999).



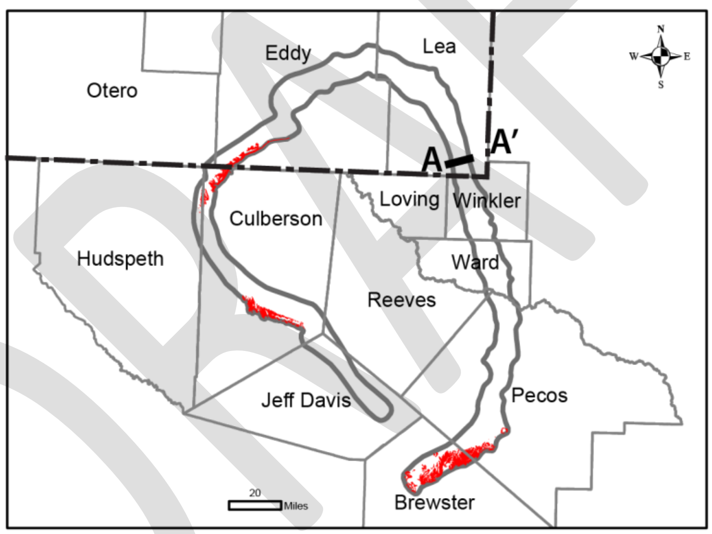
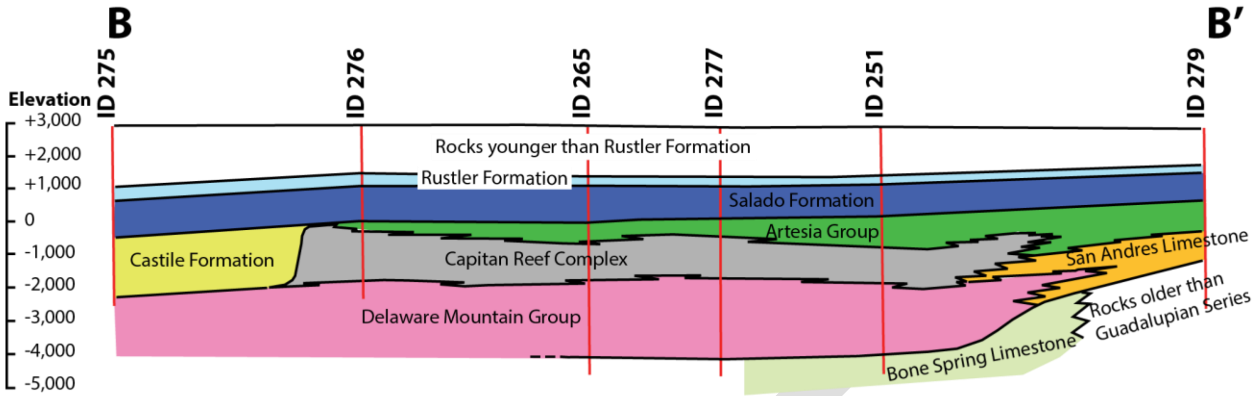


Figure 2.2.5 A-A' cross-section through the Capitan Reef Complex in Lea County, New Mexico (modified from Standen and others, 2009; Hiss, 1975).



Source: Modified from Hiss (1975)

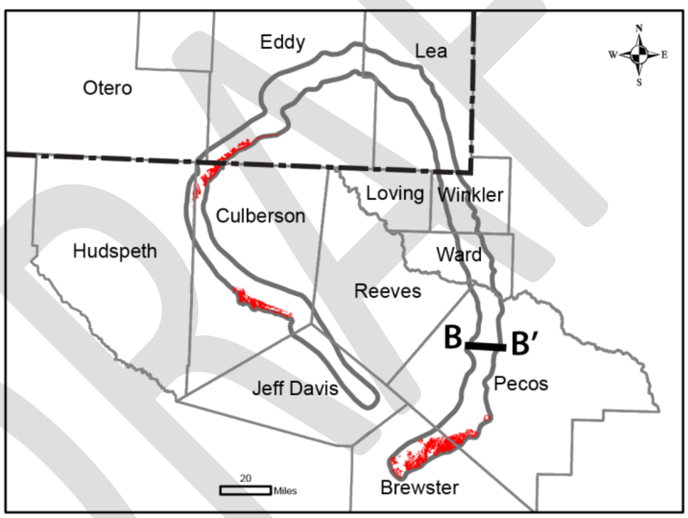


Figure 2.2.6 B-B' cross-section through the Capitan Reef Complex in Pecos County, Texas (modified from Standen and others, 2009; Hiss, 1975).

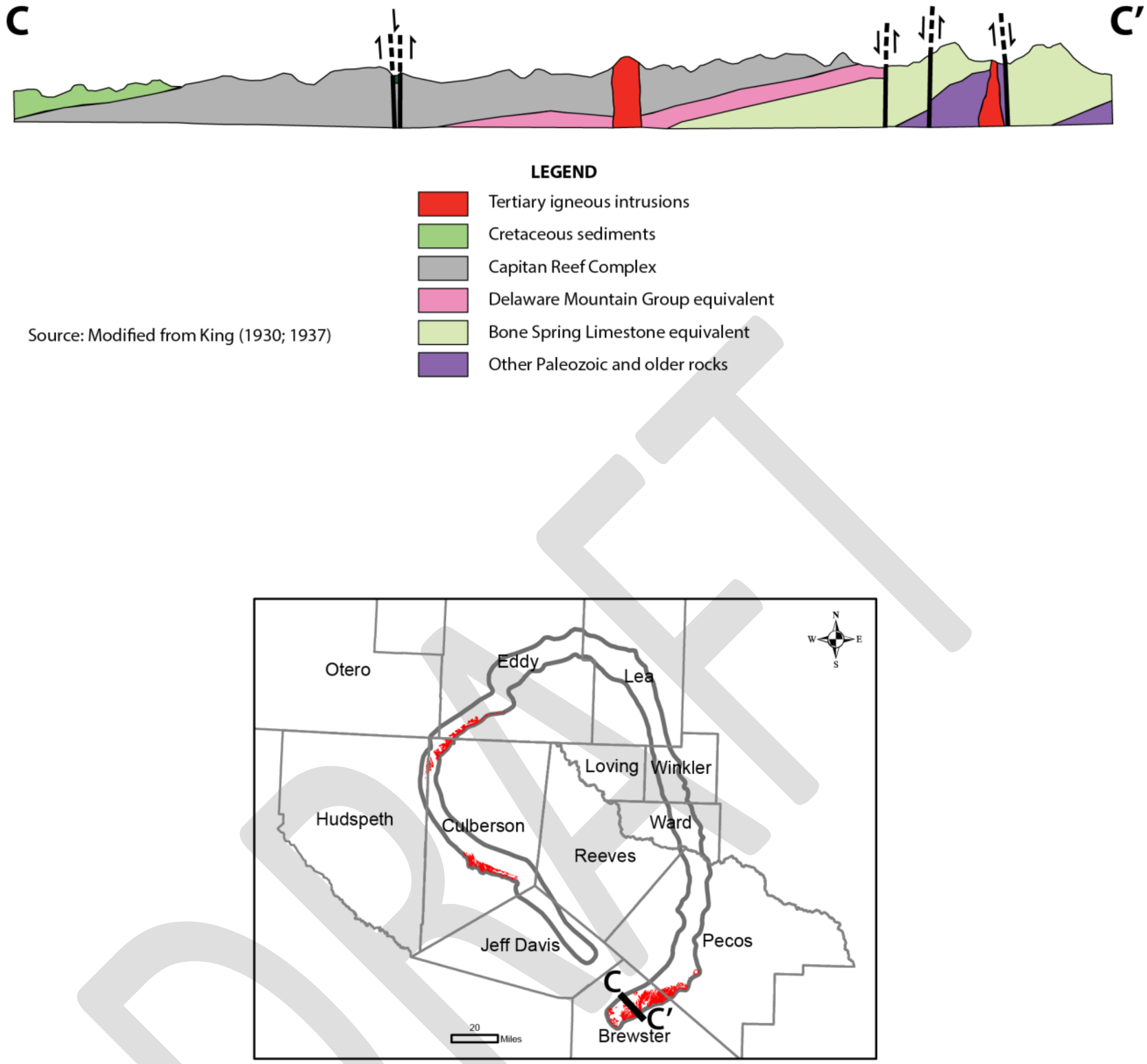


Figure 2.2.7 C-C' cross-section through the Capitan Reef Complex outcrop in the Glass Mountains, Brewster County, Texas (modified from Standen and others, 2009; King, 1930; 1937).

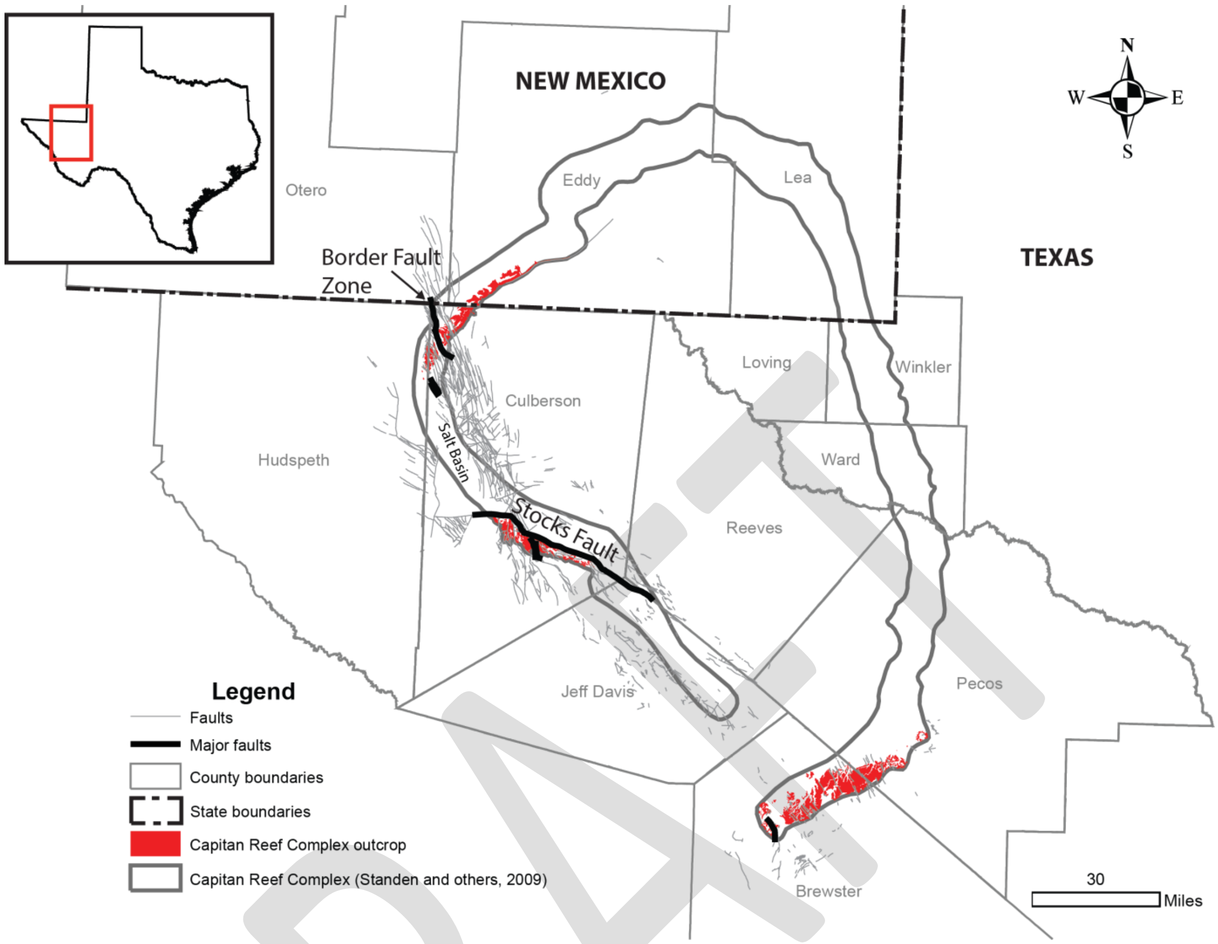


Figure 2.2.8 Faults that cut through or lie adjacent to the Capitan Reef Complex Aquifer.

3.0 PREVIOUS WORK

There have been several studies of the stratigraphy, geologic framework, and hydrogeology of the Capitan Reef Complex—mostly by the United States Geological Survey and the University of Texas at Austin. Studies by King (1948), Hayes (1964), Wood (1965), and Bebout and Kerans (1993) described the geology of the Capitan Reef Complex outcrops in the Guadalupe and Apache mountains. Standen and others (2009) compiled work on the stratigraphy and geologic framework of the Capitan Reef Complex. Standen and others (2009) also used geophysical logs to define the elevations of the top and base of the Capitan Reef Complex and revise its spatial extents.

Several studies investigated the hydrogeology of the Capitan Reef Complex Aquifer, include Armstrong and McMillion (1961), White (1971), Hiss (1975; 1980), Richey and others (1985), Sharp (1989), Ashworth (1990), Brown (1997), Uliana (2001), Uliana and Sharp (2001), and INTERA (2013). The Brown (1997) study investigated water quality in the Capitan Reef

Complex Aquifer. The groundwater flow system of the Capitan Reef Complex Aquifer has been documented in work by Hiss (1980), Uliana (2001), and Uliana and Sharp (2001).

Two groundwater flow models have been constructed simulating groundwater flow in parts of the Capitan Reef Complex Aquifer (Figure 3.0.1). The first groundwater flow model simulates groundwater flow through the Capitan Reef Complex Aquifer and Pecos River alluvium near Carlsbad, New Mexico (Barroll and others, 2004). A simplified groundwater flow model was constructed by INTERA and Cook-Joyce (2012) simulating groundwater flow in part of the eastern arm of the Capitan Reef Complex Aquifer. The purpose of that model was to simulate the potential effects of a well field located in central Ward County. Consequently, despite its regional extent, this model was calibrated based on water-level and pumping data from well fields located within Ward and Winkler counties. The groundwater flow models by Barroll and others (2004) and INTERA and Cook-Joyce (2012) were constructed to address localized issues, groundwater flow along the Pecos River and potential effects of a well field, respectively. This contrasts with the proposed TWDB groundwater availability model of the eastern arm of the Capitan Reef Complex Aquifer that will be designed to simulate groundwater flow between the Glass Mountains outcrop in Brewster County and where the Pecos River interacts with the aquifer near Carlsbad, New Mexico—a study area that includes the areas of interest of both models.

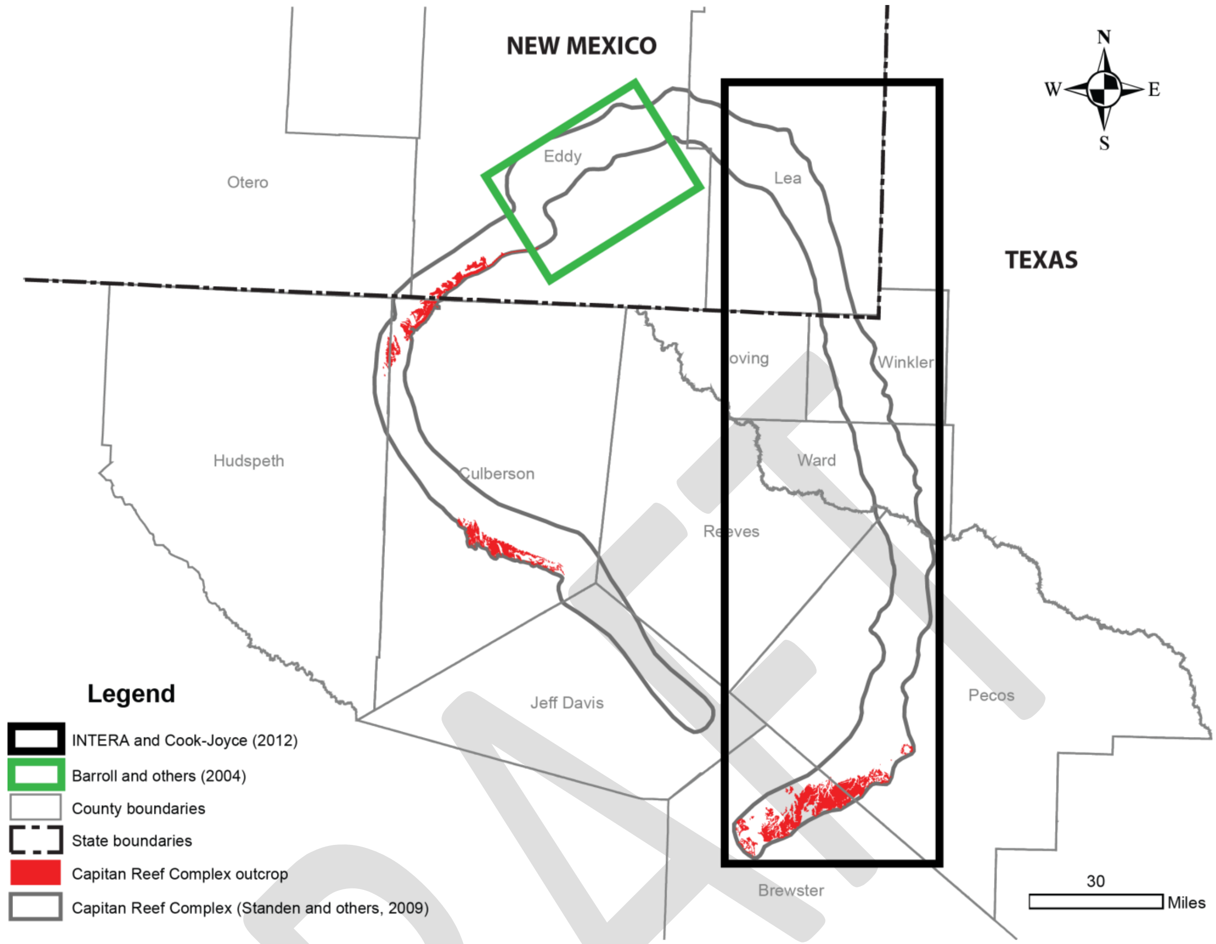


Figure 3.0.1 Approximate extents of previous model grids for models used for simulating groundwater flow through the Capitan Reef Complex Aquifer.

4.0 HYDROLOGIC SETTING

The hydrogeologic setting is a description of the factors that contribute to the groundwater hydrology of the Capitan Reef Complex Aquifer. These factors include the hydrostratigraphy, hydrogeologic framework, water levels and regional groundwater flow, recharge, surface water bodies, hydraulic properties, discharge, and water quality.

4.1 Hydrostratigraphy and Hydrostratigraphic Framework

The Capitan Reef Complex Aquifer (Figure 2.2.3) is defined as Permian-age carbonate reef-forming rocks that include the Goat Seep Limestone, Capitan Limestone, and Carlsbad Limestone (Hiss, 1975). In the eastern section of the Capitan Reef Complex near the Glass Mountains, equivalent rocks include the Vidrio and Tessey formations described by King (1930) and Hill (1996) are also included in the aquifer. The Munn Formation underlies the Capitan Reef Complex in the Apache Mountains, is up to 450 feet thick and consists primarily of a thinbedded dolomite and is the stratigraphic equivalent of the Goat Seep Limestone and Vidrio Formation (Barnes and others, 1968; Wood, 1968; Hiss, 1975).

The Capitan Reef Complex Aquifer is comprised of sediments of the limestone formations that made up a Permian reef complex on the margins of the Delaware Basin (Figure 4.1.1). These limestone formations include the Capitan Limestone in the western and northern parts of the reef complex, the Carlsbad Limestone and Goat Seep Dolomite in the north, and the Tessey and Vidrio formations in the south. The Capitan Reef Complex Aquifer is bounded laterally and vertically by aquitards made up of the fore-reef Artesia Group and back-reef Delaware Mountain Group. These stratigraphic units are in turn overlain by the evaporites of the Castile and Salado formations that also act as aquitards. Four aquifers—the Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers—also overlie the aquitards.

The top of the Capitan Reef Complex Aquifer has elevations ranging from 1,500 feet below mean sea level to more than 8,000 feet above mean sea level. The top surface of the Capitan Reef Complex Aquifer shown in Figure 4.1.2 is a combination of subsurface top designations using geophysical logs and driller's reports, and 30-meter digital elevation model surface elevations of the Capitan Reef Complex Aquifer outcrops (Standen and others, 2009). Outcrop structural tops within the Capitan Reef Complex Aquifer were identified using the available digital Geological Atlas of Texas (Pearson, 2007). The subsurface top of the Capitan Reef Complex Aquifer is a combination of structural tops and erosional surfaces. Figure 4.1.3 shows the base of the Capitan Reef Complex Aquifer. The Capitan Reef Complex Aquifer base was created by subtracting the Capitan Reef Complex Aquifer thickness (Figure 4.1.4) from the top surface (Figure 4.1.2) using ArcGIS Spatial Analyst (Standen and others, 2009).

Figures 4.1.2 and 4.1.3 indicate that the Capitan Reef Complex Aquifer dips to the northeast with highest elevations associated with outcrops in the Guadalupe and Glass mountains and lowest elevations occurring in Lea, Winkler, Ward and northern Pecos counties. The thickest parts of the Capitan Reef Complex Aquifer occur in the Guadalupe Mountains and in the northern and eastern parts of the reef complex (Figure 4.1.4). The thickest areas occur on the fore-reef side of the Capitan Reef Complex. The thinnest parts of the Capitan Reef Complex Aquifer occur in the southern and back-reef parts of the reef complex.

The Capitan Reef Complex locally underwent erosion during the middle to late Guadalupian period. Hiss (1975) identified Capitan Reef Complex carbonate reef highs—thick carbonate intervals—alternating with erosional valleys—thin carbonate intervals—on the eastern arm of the Capitan Reef Complex (Figure 4.1.4). These erosional valleys extended from the Central Basin Platform, through the Capitan Reef Complex and toward the Delaware Basin (Figure 4.1.4). These erosional valleys were in-filled with silts, clays, and fine sands forming clastic channels overlying and adjacent to the Capitan Reef Complex limestone.

The elevations of the top and base of the Rustler Aquifer are shown in Figures 4.1.5 and 4.1.6. These figures indicate low areas coinciding with the Monument Draw and Pecos basins that are most commonly associated with the overlying Pecos Valley Aquifer (Jones, 2001; 2004). These basins formed due to dissolution of the underlying Salado Formation. The Monument Draw also coincides with the Capitan Reef Complex. The base of the Rustler Aquifer coincides with the top of the Salado Formation which is the top of the underlying aquitards that separate the Capitan Reef Complex Aquifer and the overlying Rustler Aquifer. Figure 4.1.7 shows that the Rustler Aquifer is thickest on the basin side of the Capitan Reef Complex—300 to 600 feet thick—while on the shelf side of the Capitan Reef Complex it thins to less than 100 feet.

Like the underlying Rustler Aquifer, the Dockum Aquifer top and base display low areas coinciding with the Monument Draw and Pecos basins (Figures 4.1.8 and 4.1.9). The combined thickness of the Dockum Group and Dewey Lake Formation indicate an area of increased thickness coinciding with the Monument Draw and underlying Capitan Reef Complex (Figure 4.1.10).

The Monument Draw and Pecos basins are not apparent at land surface that forms the tops of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Figure 4.1.11). However, these basins are apparent as low areas at the base of the respective aquifers and as areas of increased thickness (Figures 4.1.12 and 4.1.13).

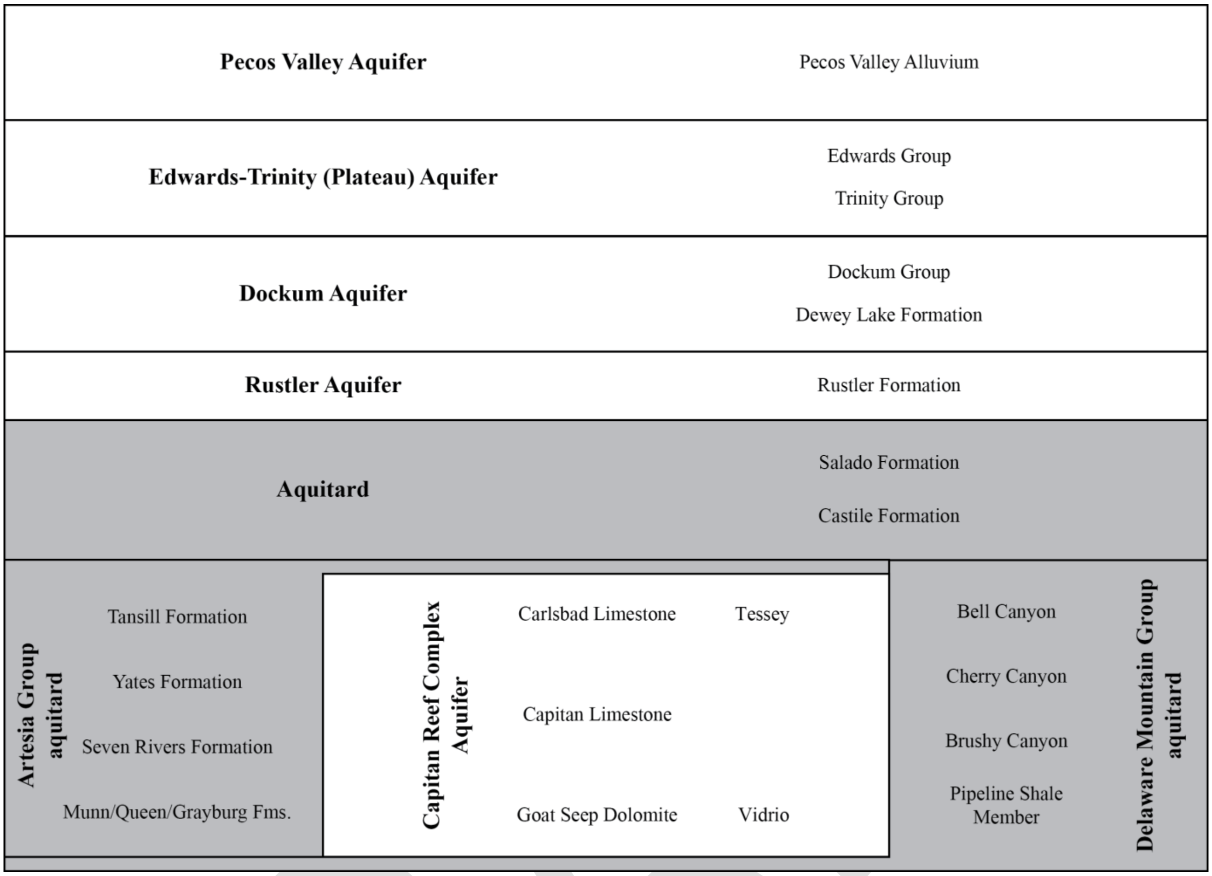


Figure 4.1.1 Hydrostratigraphic chart of the Capitan Reef Complex and overlying and underlying formations.

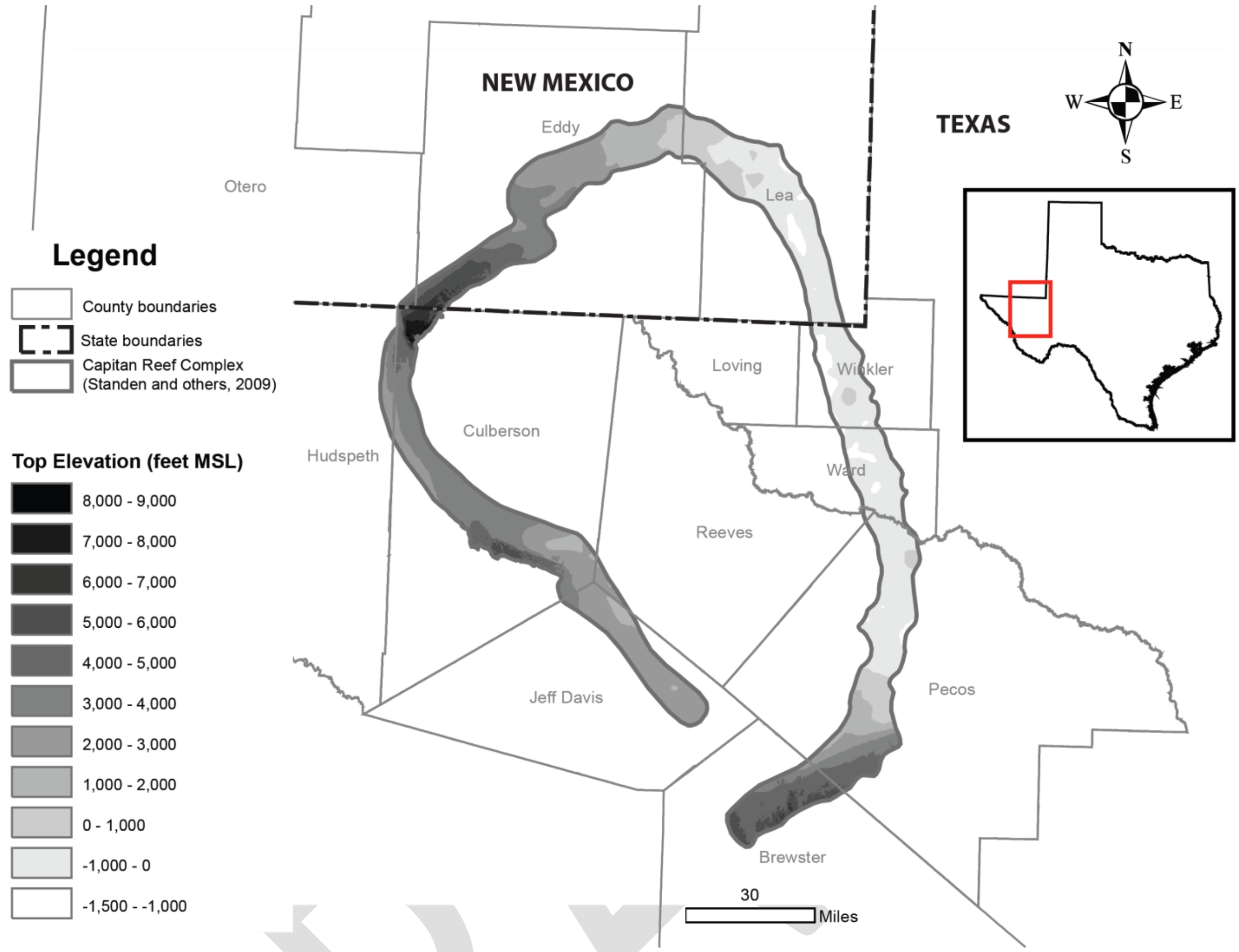


Figure 4.1.2 The elevation (in feet above mean sea level (MSL)) of the top of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).

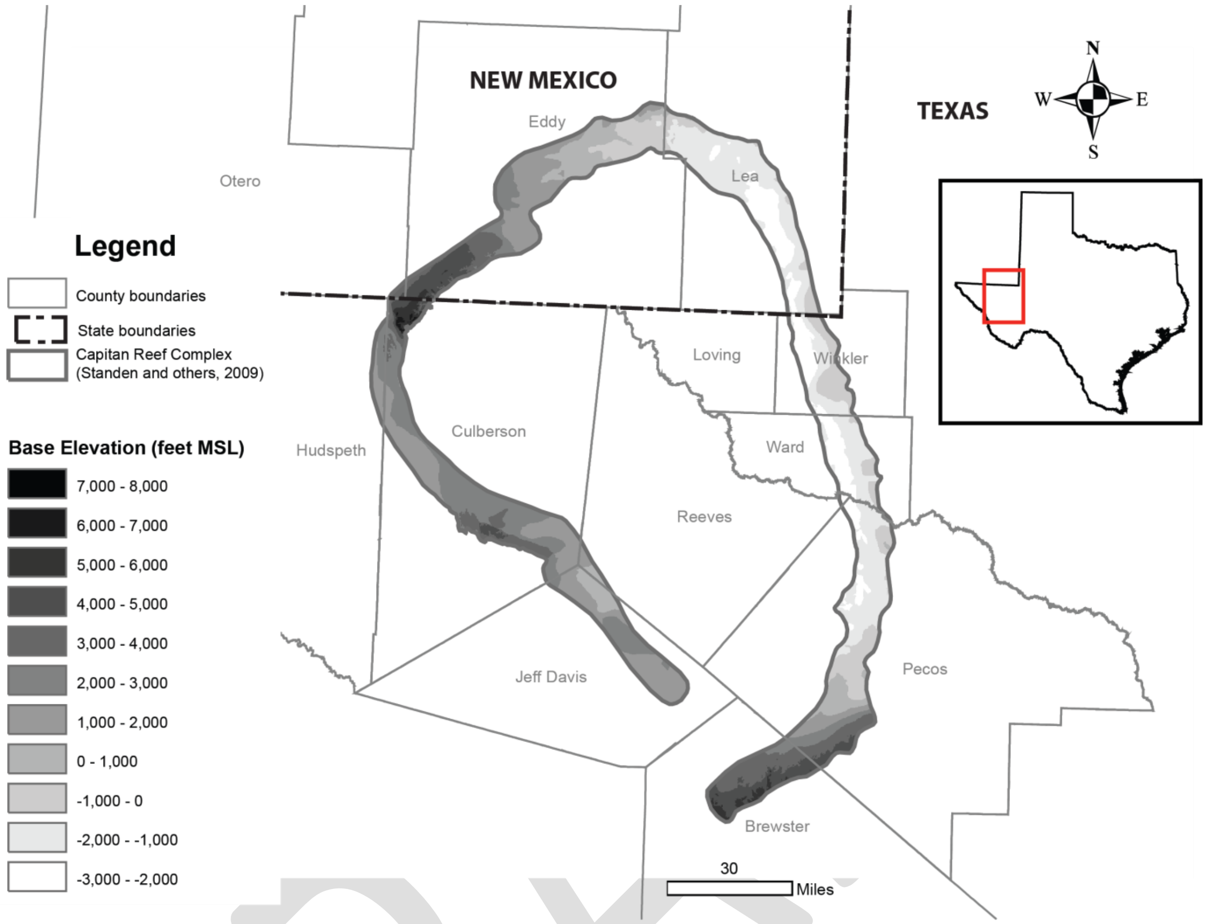


Figure 4.1.3 The elevation (in feet above mean sea level (MSL)) of the base of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).

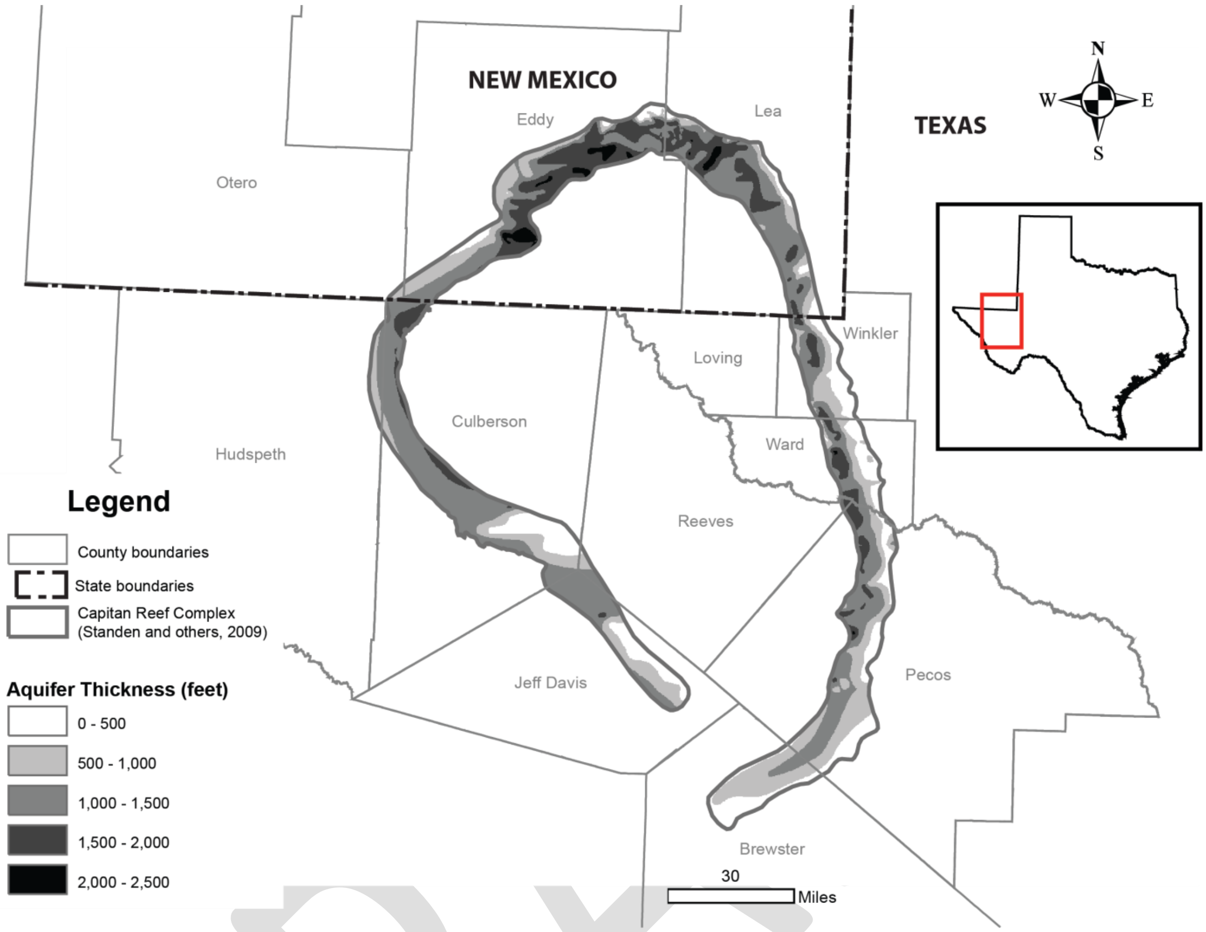


Figure 4.1.4 Thickness (in feet) of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).

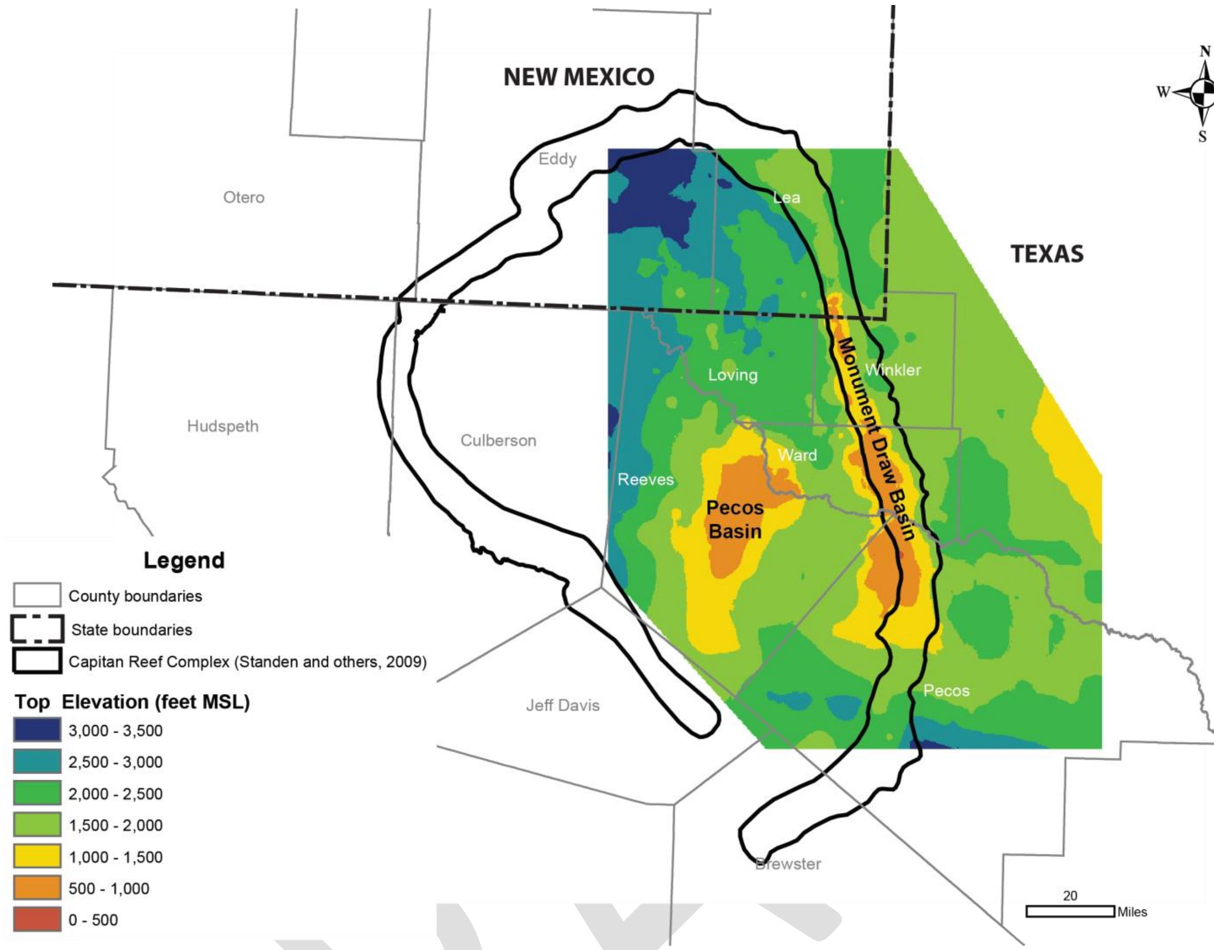


Figure 4.1.5 The elevation (in feet above mean sea level (MSL)) of the top of the Rustler Aquifer (based on data from Ewing and others, 2012).

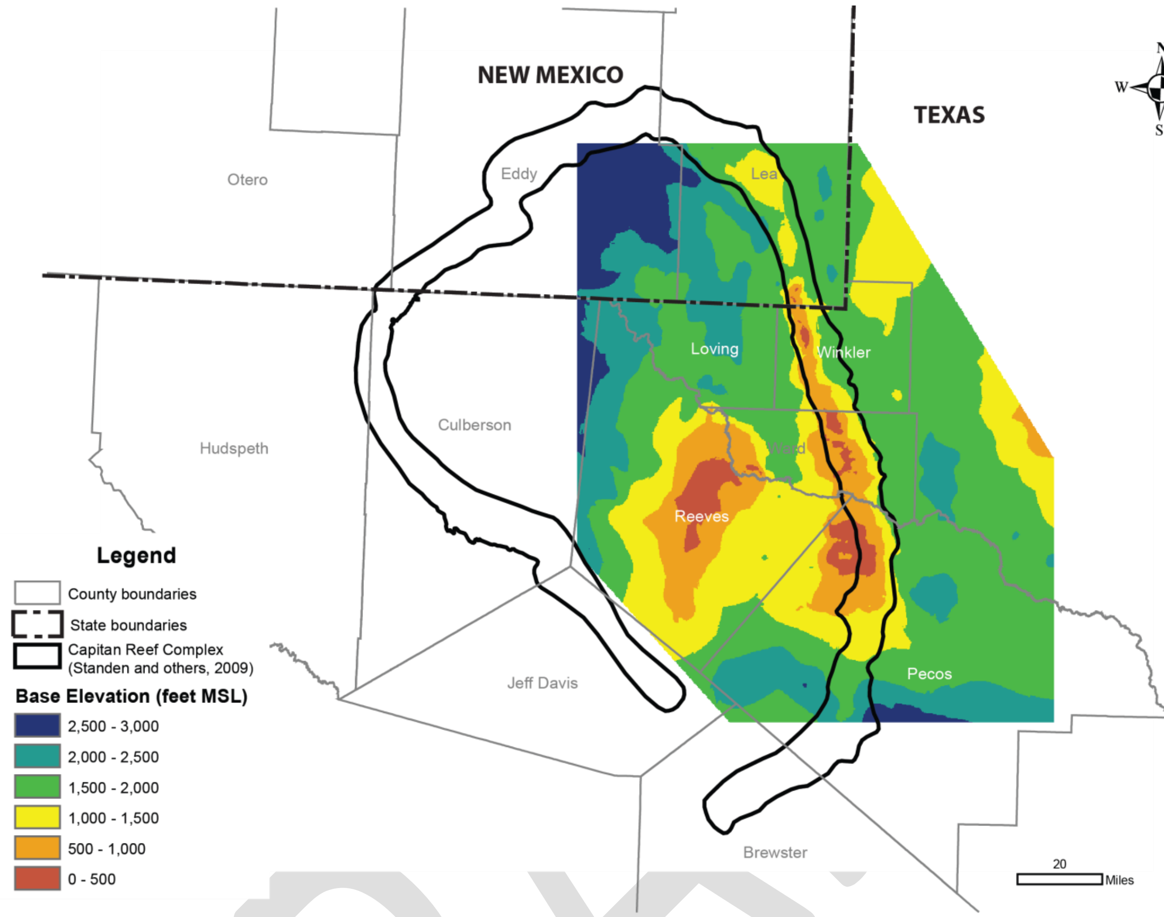


Figure 4.1.6 The elevation (in feet above mean sea level(MSL)) of the base of the Rustler Aquifer (based on data from Ewing and others, 2012).

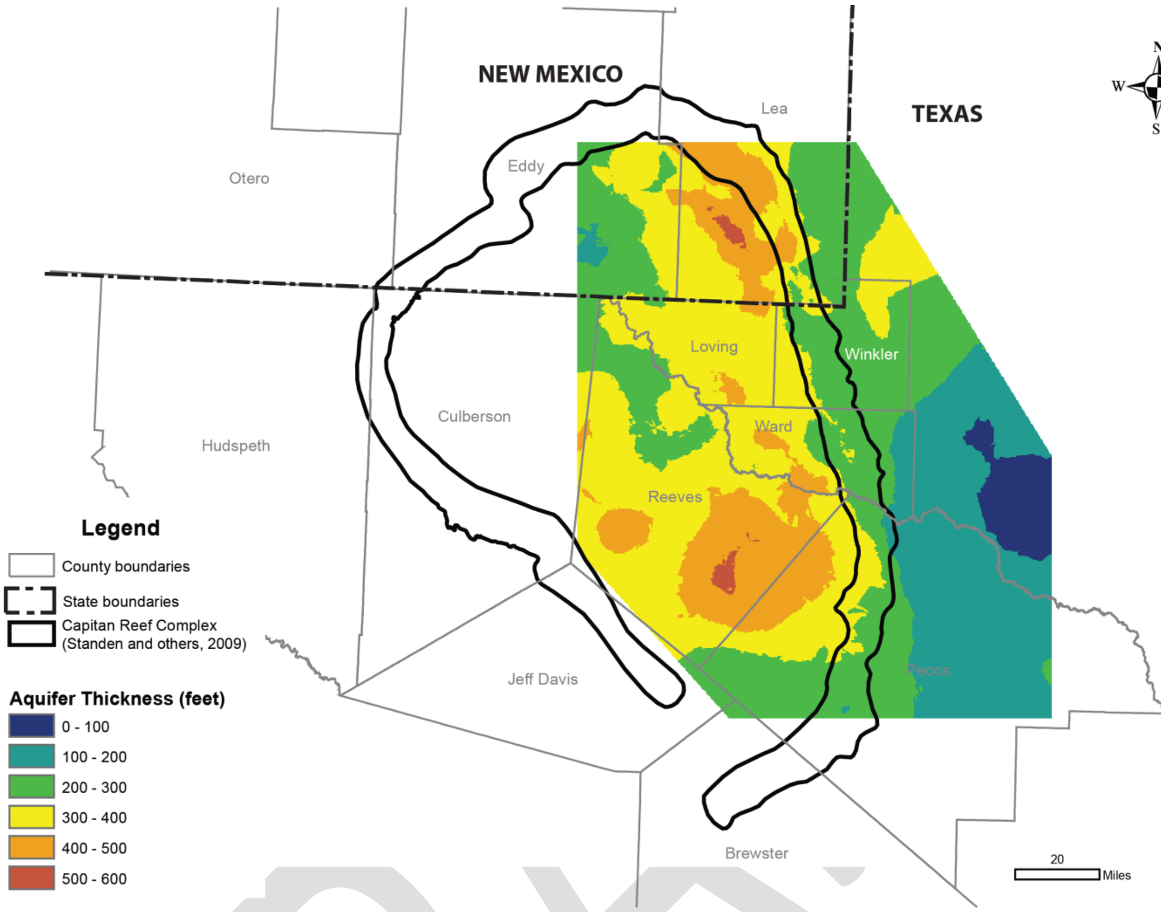


Figure 4.1.7 Thickness (in feet) of the Rustler Aquifer (based on data from Ewing and others, 2012).

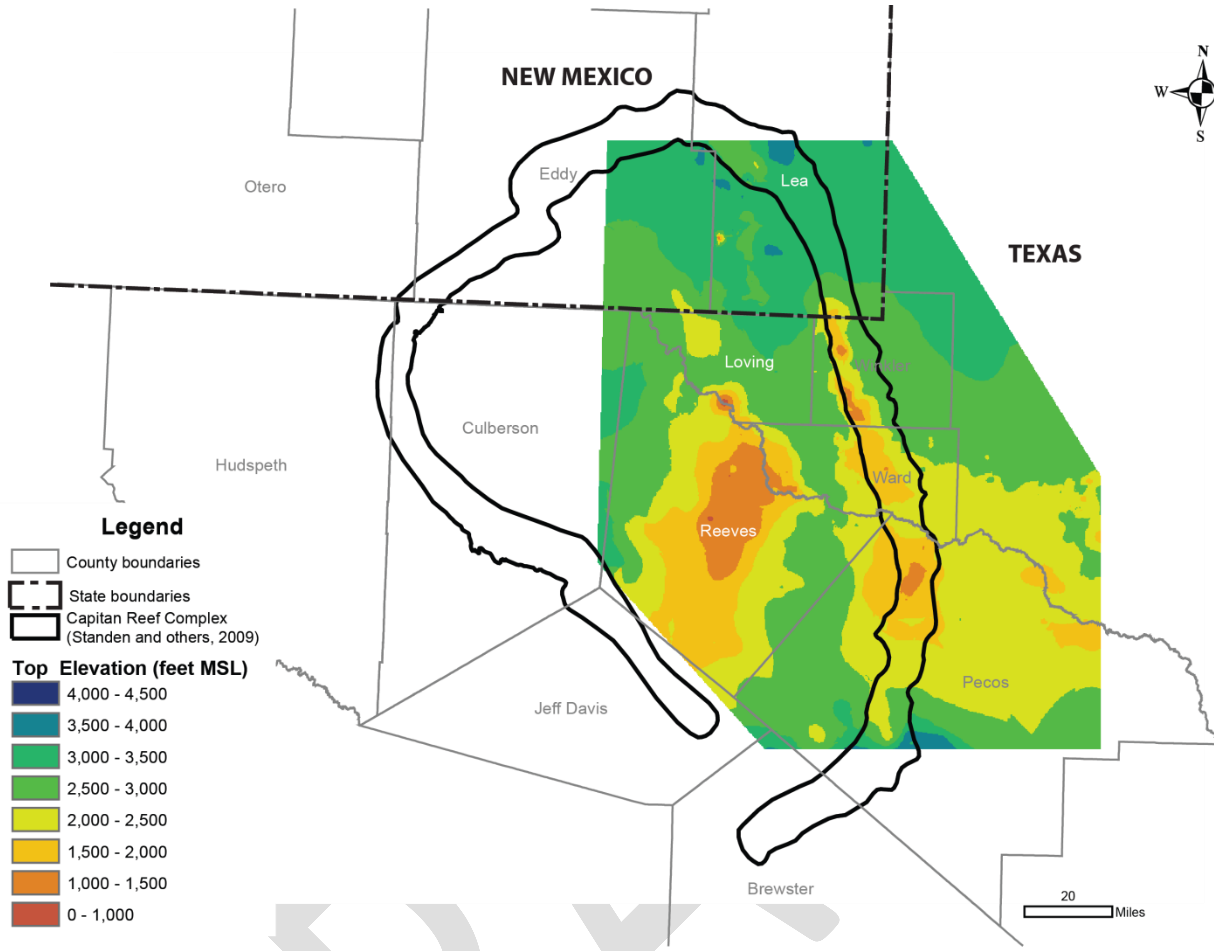


Figure 4.1.8 The elevation (in feet above mean sea level (MSL)) of the top of the Dockum Aquifer (based on data from Ewing and others, 2012).

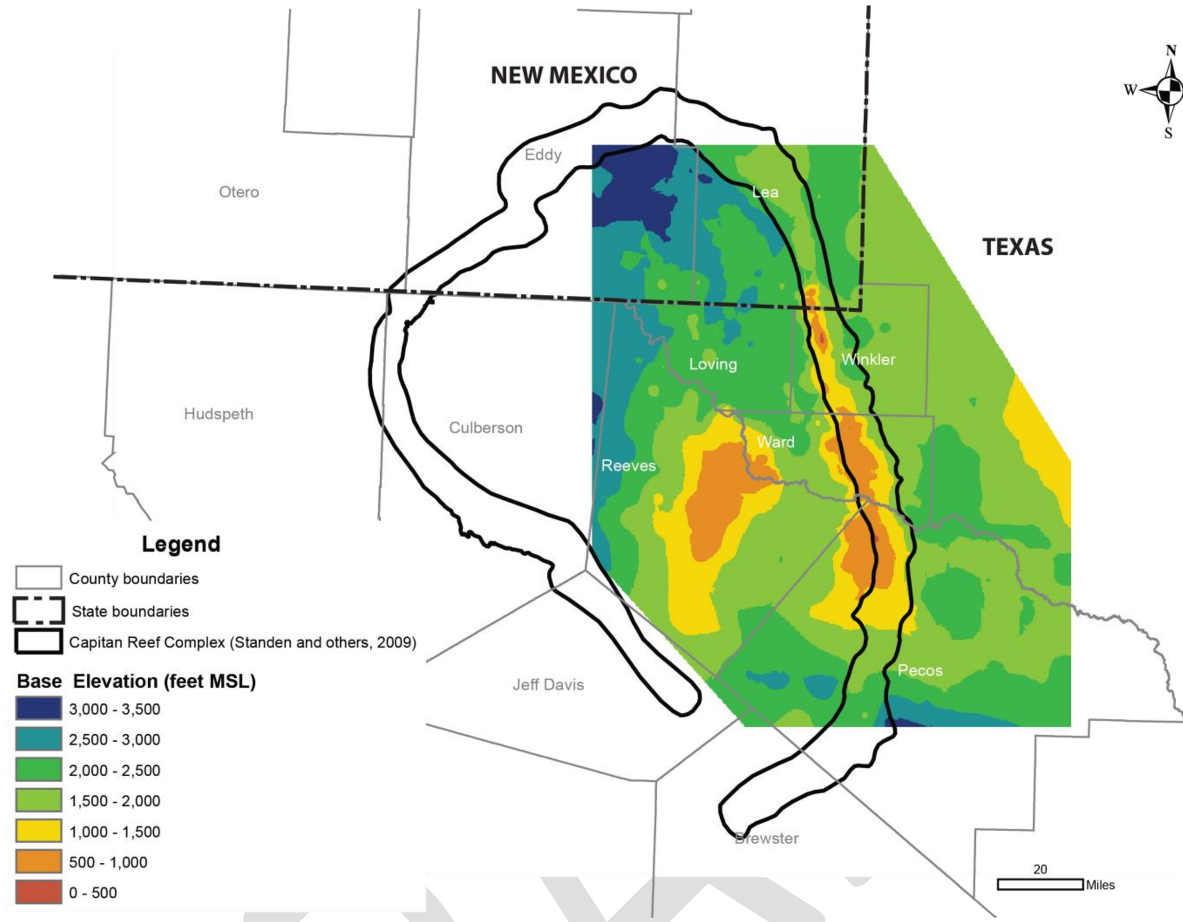


Figure 4.1.9 The elevation (in feet above mean sea level (MSL)) of the base of the combined Dewey Lake Formation and Dockum Aquifer (based on data from Ewing and others, 2012).

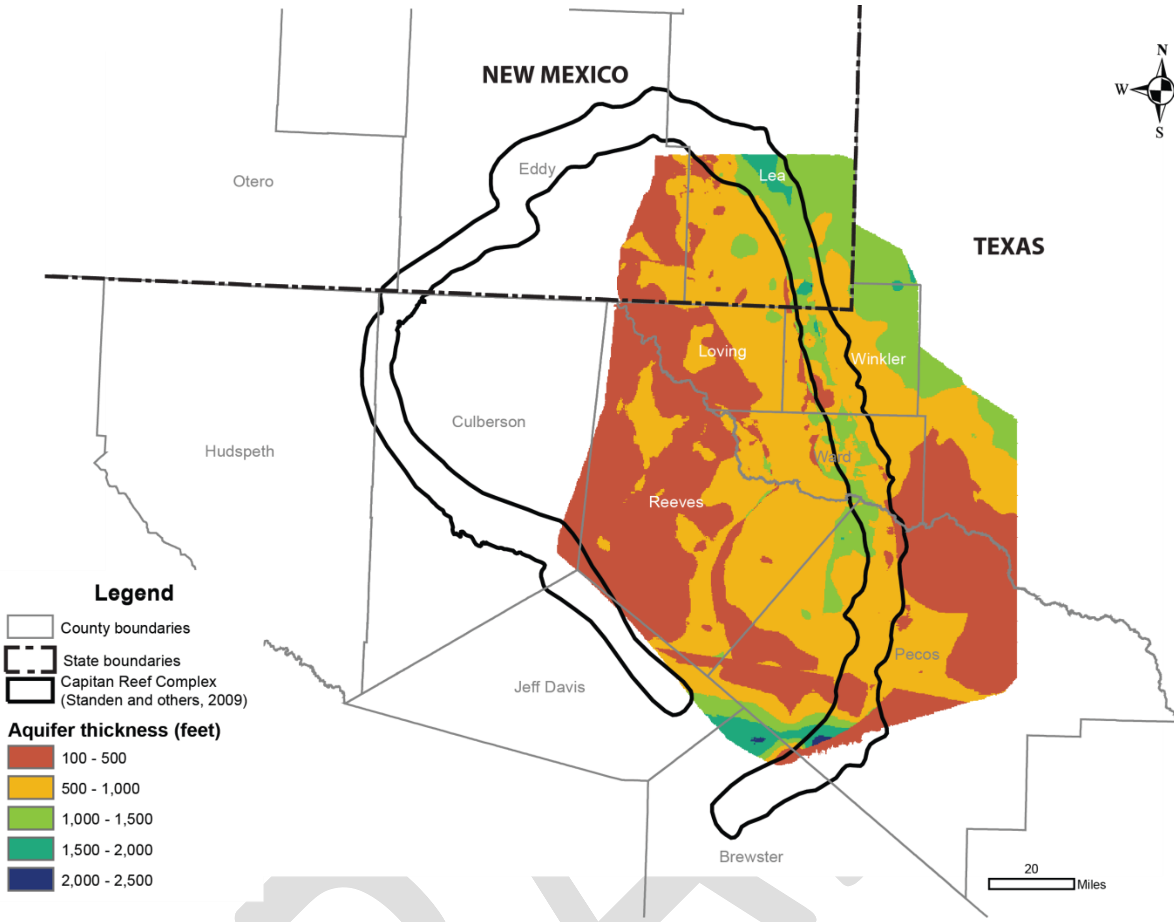


Figure 4.1.10 Total thickness (in feet) of the Dewey Lake Formation and the Dockum Aquifer (modified from Ewing and others, 2012).

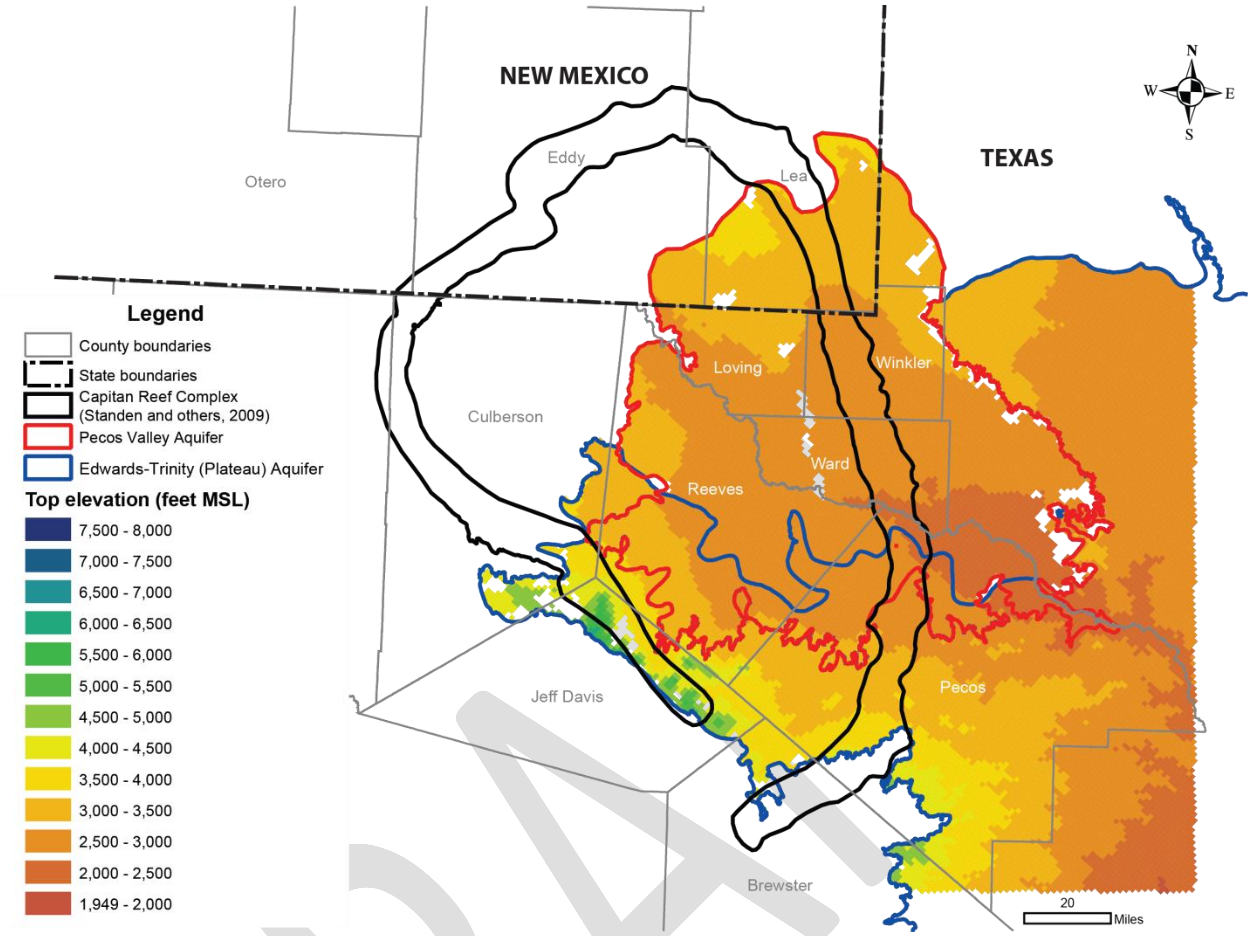


Figure 4.1.11 The elevation (in feet above mean sea level (MSL)) of the top of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (modified from Hutchison and others, 2011).

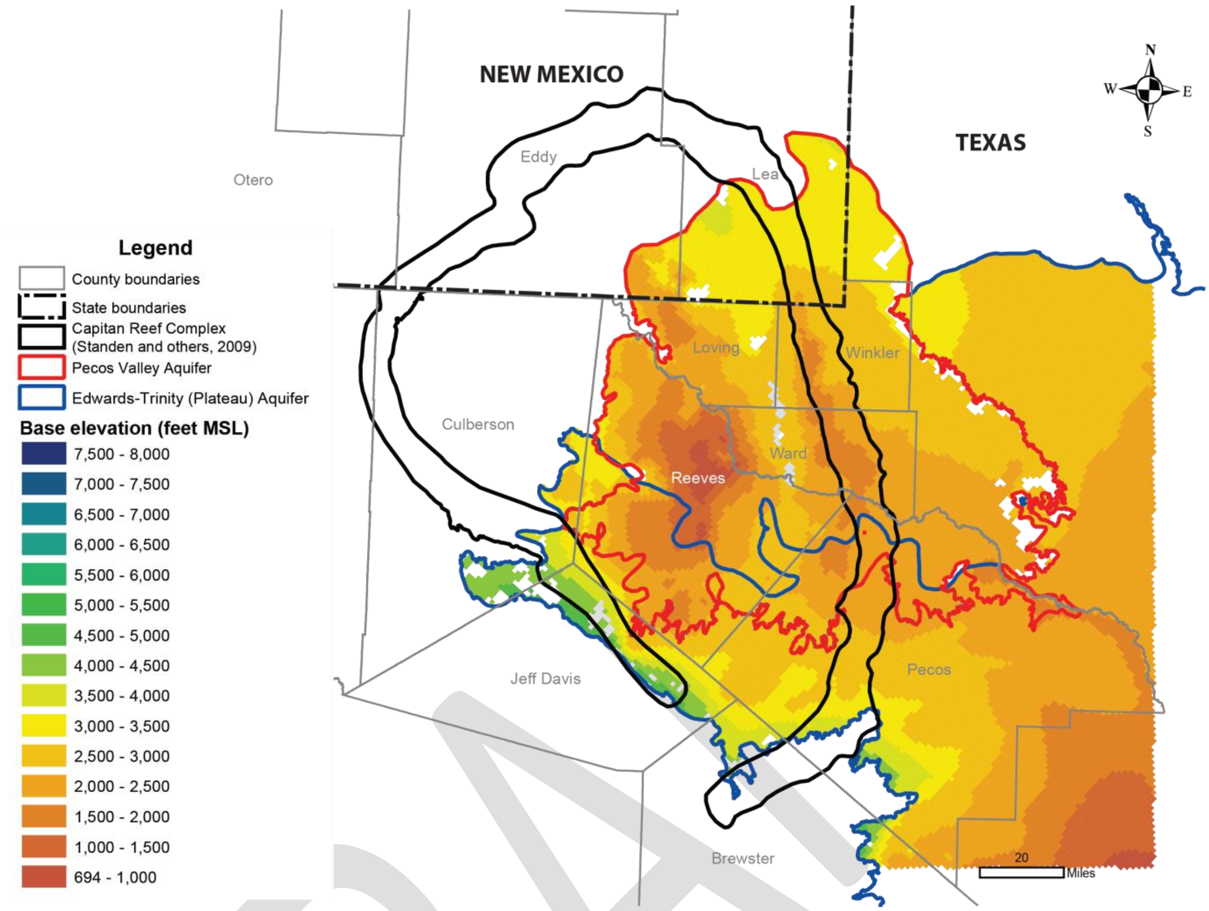


Figure 4.1.12 The elevation (in feet above mean sea level (MSL)) of the base of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (modified from Hutchison and others, 2011).

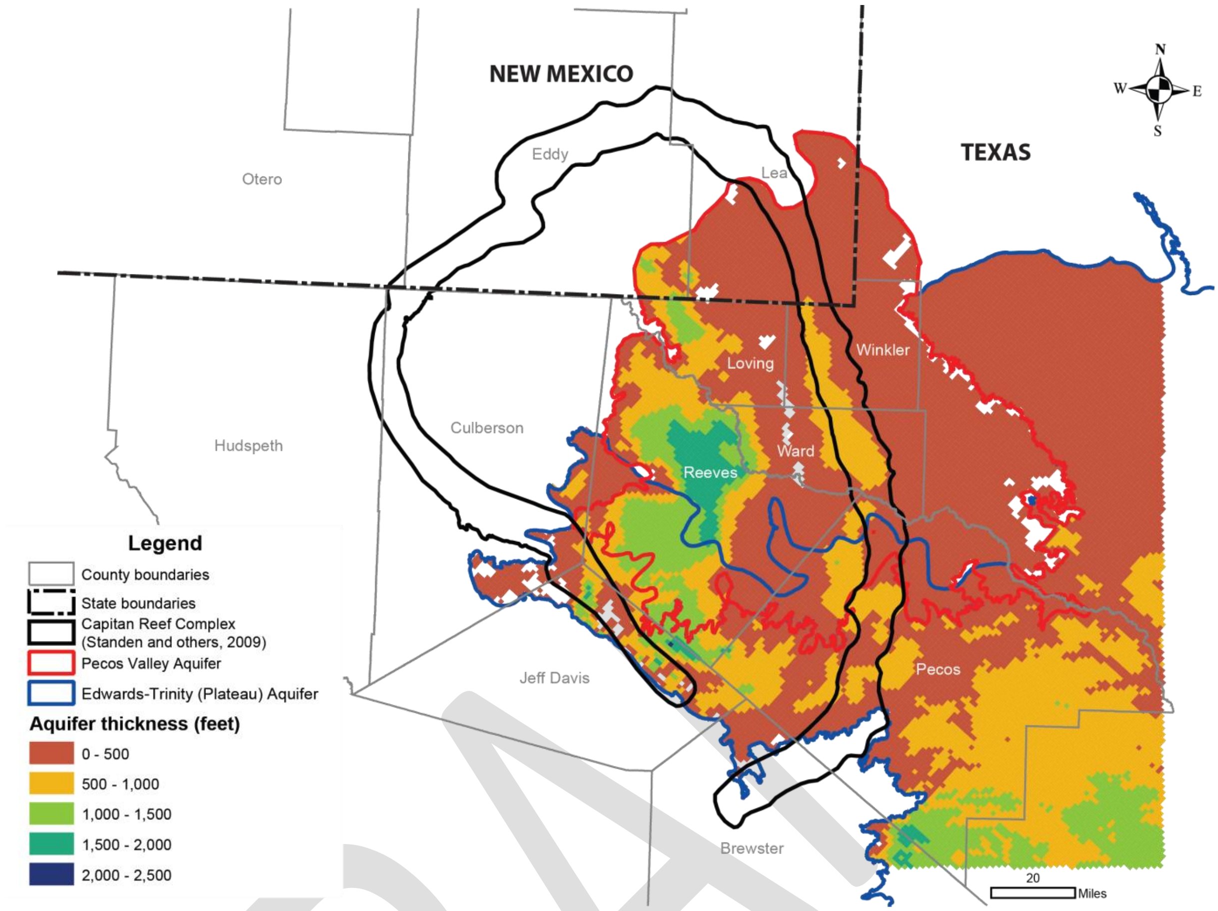


Figure 4.1.13 Thickness (in feet) of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (modified from Hutchison and others, 2011).

4.2 Water Levels and Regional Groundwater Flow

Figure 4.2.1 illustrates regional groundwater flow paths for the Capitan Reef Complex Aquifer (Hiss, 1976; 1980; Uliana, 2001; Sharp, 2001). Hiss (1980) and Richey and others (1985) hypothesized that the uplift of the western side of the Delaware Basin—associated with the Border Fault Zone and the resultant formation of the Guadalupe Mountains—resulted in a topographic gradient for the regional groundwater flow system.

The Border Fault Zone forms a hydrologic divide between two regional groundwater flow systems: one that flows northeast from the recharge zone in the Guadalupe Mountains and one that flows south (Figure 4.2.1). Regional groundwater also flows northward away from the Glass Mountains—another heavily faulted, topographically high Capitan Reef Complex outcrop (Figure 4.2.1). The Stocks Fault (Figure 4.2.1) is a large fault system with more than 1,000 feet of throw that bounds the northern flank of the Apache Mountains. The fault is probably the result of dissolution of Delaware Basin evaporites north of the fault forming a graben—the Salt basin—between the Stocks and Border fault zones (Wood, 1965; LaFave, 1987). The direction of greatest permeability is sub-parallel to the Stocks Fault (Sharp 2001; Uliana, 2000). Regional groundwater flow is probably fracture controlled and is believed to occur from Wild Horse Flat—located immediately west of the Apache Mountains—eastward through the basin sediments underneath the Apache Mountain Capitan Reef Complex outcrop or through the down-faulted Capitan Reef Complex along the northeastern side of the Stocks Fault and toward the Toyah Basin (LaFave, 1987; LaFave and Sharp, 1990; Uliana, 2000; Finch and Armour, 2001). Some of this groundwater may eventually discharge from the San Solomon Spring System located east of the Capitan Reef Complex Aquifer in Reeves and Jeff Davis counties (Chowdhury and others, 2004).

Regional groundwater flow in the Salt Basin portion of the Capitan Reef Complex is believed to occur from the down-thrown side of the Border Fault Zone in the Guadalupe Mountains to the Apache Mountains and may not be influenced by the groundwater divides apparent in the overlying alluvial aquifer (Finch and Bennett, 2002).

The groundwater flow in the eastern portion of the Capitan Reef Complex Aquifer—east of the Border Fault Zone—has probably changed in response to the incision by the Pecos River down through the Capitan Reef Complex Aquifer rocks (Hiss, 1980; Uliana, 2001). This incision took place during the Pliocene—2 to 5 million years ago—when a period of regional uplift caused rivers to erode downward and upstream (Gutentag and others, 1984). The incision of the Pecos River resulted in reduced groundwater flow east of where the Capitan Reef Complex Aquifer intersects with the Pecos River in New Mexico (Figure 4.2.2). The reduced groundwater flow is due to direct and indirect effects of the river. The direct effects occur due to discharge from springs where the Capitan Reef Complex Aquifer crops out along the Pecos River near Carlsbad, New Mexico. The indirect effects occur due to induced upward inter-aquifer flow related to discharge to the Pecos River from overlying aquifers, such as the Pecos Valley, Dockum, and Rustler aquifers.

Figure 4.2.3 shows water-level data from the eastern arm of the Capitan Reef Complex Aquifer and surrounding basin and shelf stratigraphic units—fore-reef and back-reef facies, respectively. The water-level contours suggest: (1) eastward groundwater flow across the Delaware Basin and in the Northwestern Shelf and the Central Basin Platform; (2) clockwise groundwater flow in the Capitan Reef Complex Aquifer in New Mexico; (3) counter-clockwise groundwater flow in the Capitan Reef Complex Aquifer in Brewster, Pecos, Ward and Winkler counties; and (4) groundwater convergence in Winkler County. Continuity of water-level contours in the Capitan Reef Complex Aquifer and the basin and shelf stratigraphic units west of the Pecos River in New Mexico suggest hydrologic connections between the stratigraphic units—groundwater flow is all part of the same flow system. Elsewhere, water-level contours indicate unrelated flow systems in the Delaware Basin and Capitan Reef Complex Aquifer—indicating that there is no hydrologic connection as suggested by Bjorklund and Motts (1959) and Motts (1968). The apparent convergence of groundwater flow in Winkler County suggests: (1) discharge by cross-formational flow into the adjacent Central Basin Platform; or (2) discharge by cross-formational flow through the overlying collapse feature that formed due to dissolution of the Salado

Formation, cuts through overlying aquifers—the Rustler and Dockum aquifers—and resulted in the formation of the Monument Draw Trough in the Pecos Valley Aquifer (Jones, 2001; 2004; 2008).

Water-level data from the Capitan Reef Complex Aquifer study area are sparse. A total of 138 wells in the Capitan Reef Complex Aquifer have at least one water-level measurement, with a median of two measurements (Figure 4.2.4). There are only two wells in New Mexico—both in Eddy County—and no water-level measurements in Lea County, New Mexico and Winkler County, Texas. Figure 4.2.5 shows the temporal distribution of the Capitan Reef Complex Aquifer water-level data—mostly since 1960. About half of the wells in deepest part of the Capitan Reef Complex Aquifer—northern Pecos County and Ward County— are artesian or flowing wells (Figure 4.2.6). Water-level data shown in Figure 4.2.7 generally agree with the groundwater flowpaths proposed by Hiss (1980). Highest water levels in the Capitan Reef Complex Aquifer occur in the Guadalupe Mountains, decreasing to the east and west. Water levels are also high in the Glass Mountains decreasing to the north and reaching minimum elevations in Ward County. Figures 4.2.8 through 4.2.10 show water-level data for the aquifers that overlie the Capitan Reef Complex Aquifer—the Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers. In the Rustler Aquifer, water-level data displayed in Ewing and others (2012) suggest groundwater flow trends from the west and south, converging on the Monument Draw Basin and Pecos River (Figure 4.2.8). Dockum Aquifer water-level data suggest groundwater flow gradients from northwest to southeast (Figure 4.2.9). Water-level data in the Edwards-Trinity (Plateau) and Pecos Valley aquifers in the Capitan Reef Complex Aquifer study area indicate groundwater flow converging on the Pecos River (Figure 4.2.10). The Pecos River is the main groundwater discharge zone for the largely surficial Edwards-Trinity (Plateau) and Pecos Valley aquifers ion the study area. Additionally, water-level data for the Pecos Aquifer indicate a cone of depression in central Reeves County attributable to irrigation pumping (Jones, 2001; 2004).

Water-level comparisons were conducted where: (1) the Capitan Reef Complex Aquifer is overlain by other aquifers—the Pecos Valley, Edwards-Trinity (Plateau), Dockum, and Rustler aquifers, and (2) there were available water data from wells located within 5 miles of a Capitan Reef Complex Aquifer well (Figure 4.2.11). Figure 4.2.12 shows the results of this comparison conducted at the five Capitan Reef Complex Aquifer locations shown in Figure 4.2.11. Inter-aquifer water-level comparisons suggest that water levels in the Capitan Reef Complex Aquifer are generally higher than the water levels in the overlying aquifers. This suggests upward hydraulic gradients and groundwater flow from the Capitan Reef Complex Aquifer to the overlying aquifers.

Figure 4.2.13 shows the locations with the most water-level data in each county. The total number of measurements range from 3 in Pecos County, Texas to 516 in Eddy County, New Mexico. Figures 4.2.14 and 4.2.15 show hydrographs of the transient water-level data. The hydrographs indicate: (1) gradual water-level decline over time in the western part of the Capitan

Reef Complex Aquifer—Hudspeth and Culberson counties, (2) a net water-level rise in the eastern part of the aquifer—Pecos and Ward counties, and (3) relatively constant water levels in northern part of the aquifer—Eddy County.

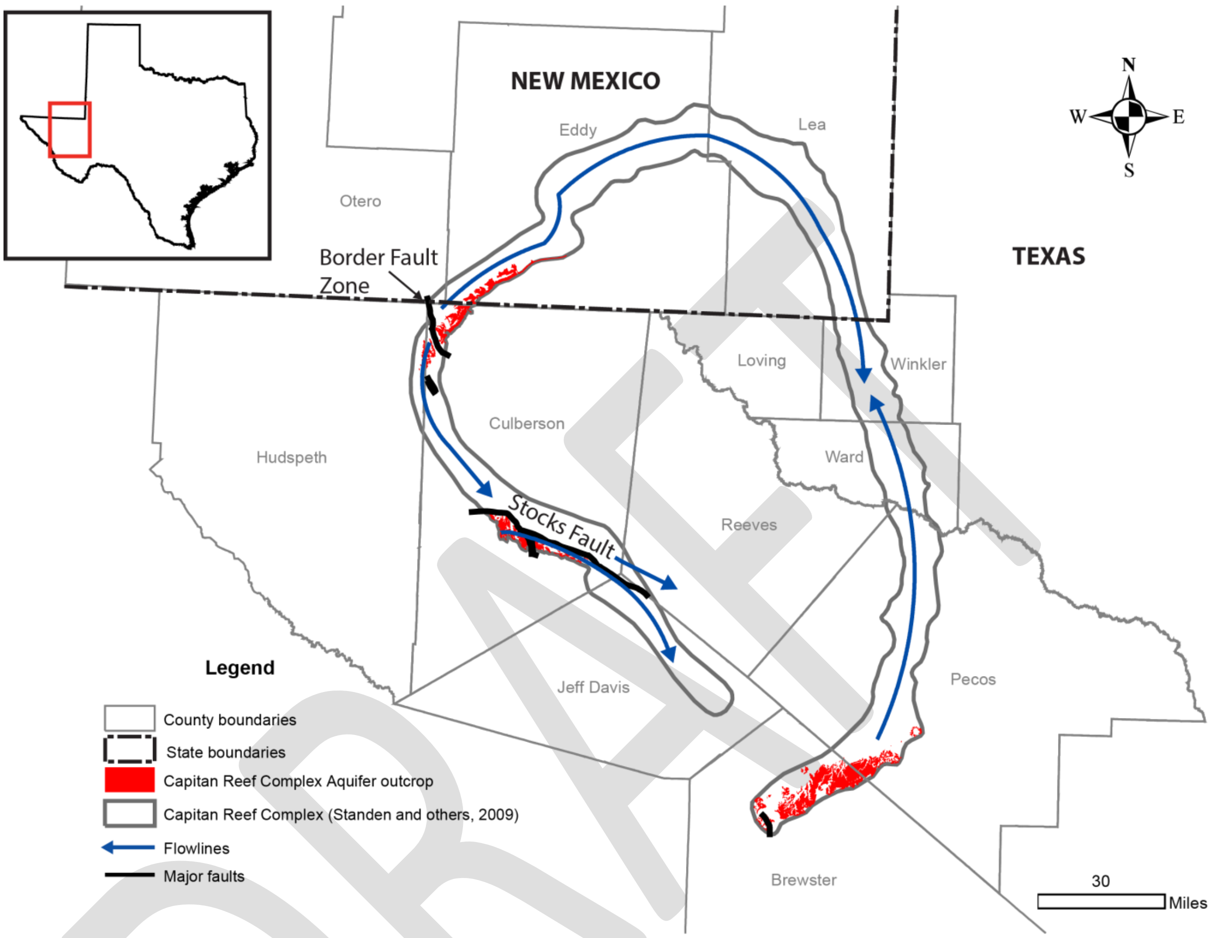


Figure 4.2.1 Conceptual diagram of the proposed flow systems in the Capitan Reef Complex Aquifer based on work by Hiss (1980) and Sharp (2001).

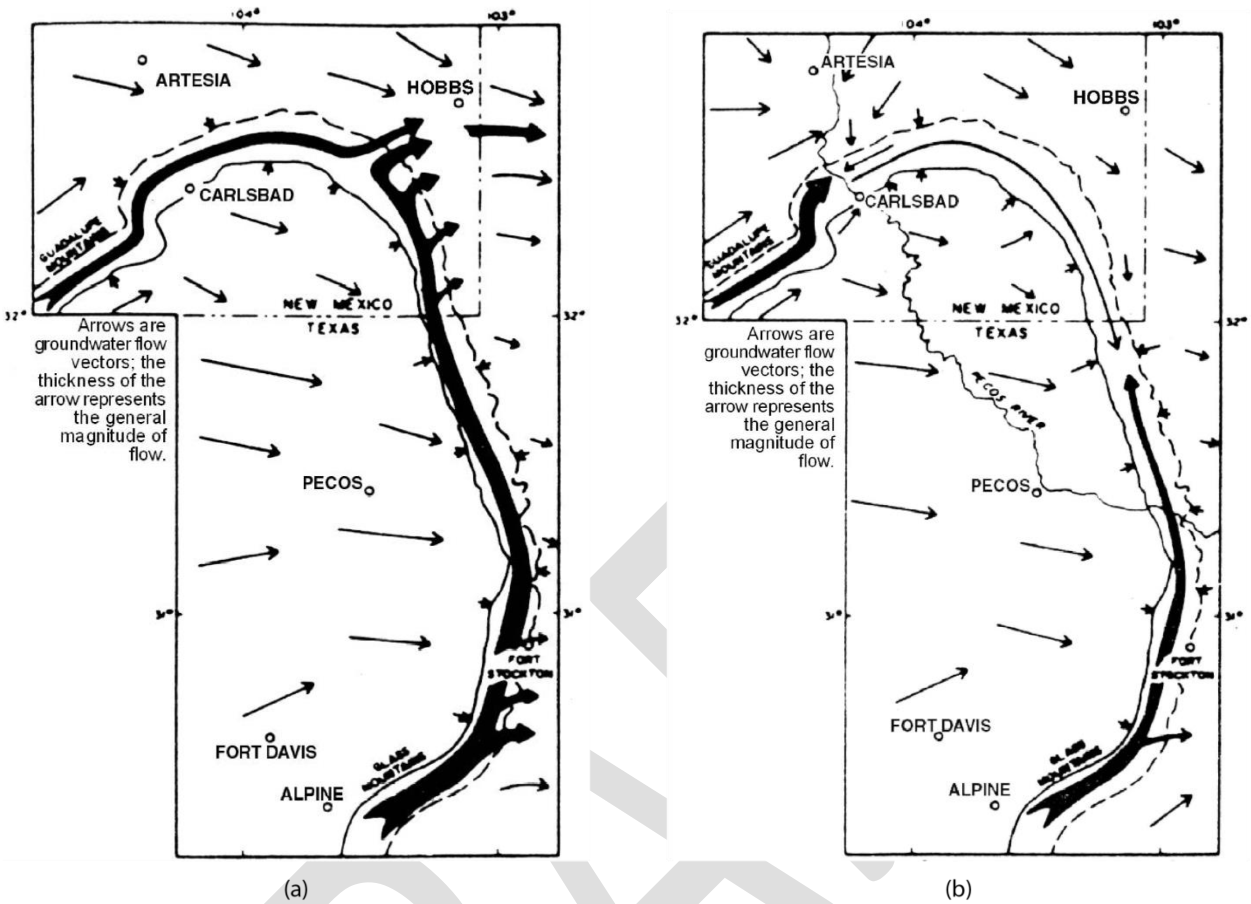


Figure 4.2.2 Groundwater flowpaths through the eastern arm of the Capitan Reef Complex Aquifer have changed over time in response to the development of the Pecos River. (a) Prior to the incision of the Pecos River, and (b) After the incision of the Pecos River. Modified from Hiss (1980).

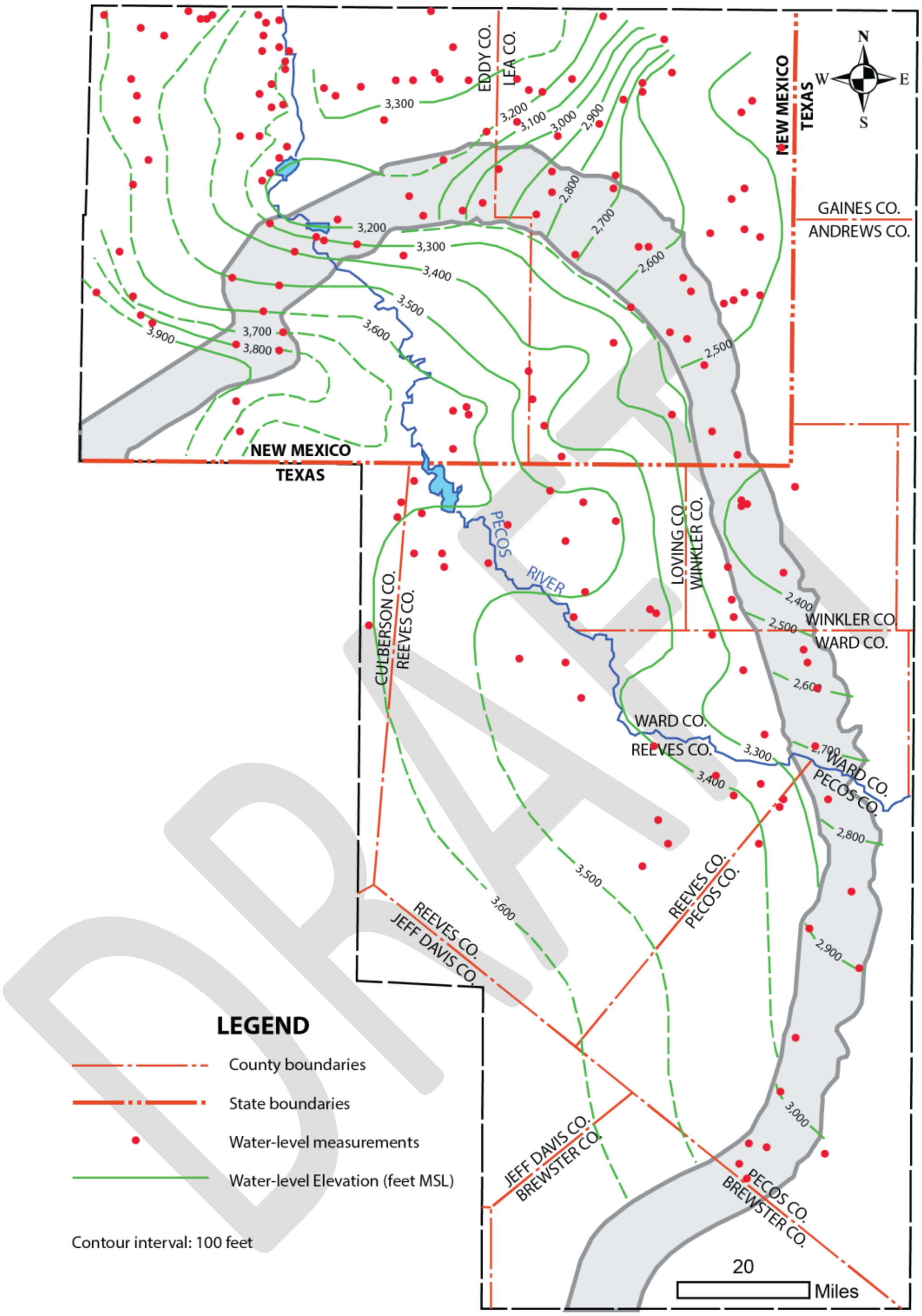


Figure 4.2.3 Post-development water levels in the Capitan Reef Complex Aquifer and surrounding basin and shelf stratigraphic units (modified from Hiss, 1980). The continuity of water-level contours in the Capitan Reef Complex Aquifer and basin and shelf stratigraphic units in Eddy County indicate hydrologic connection that does not occur elsewhere.

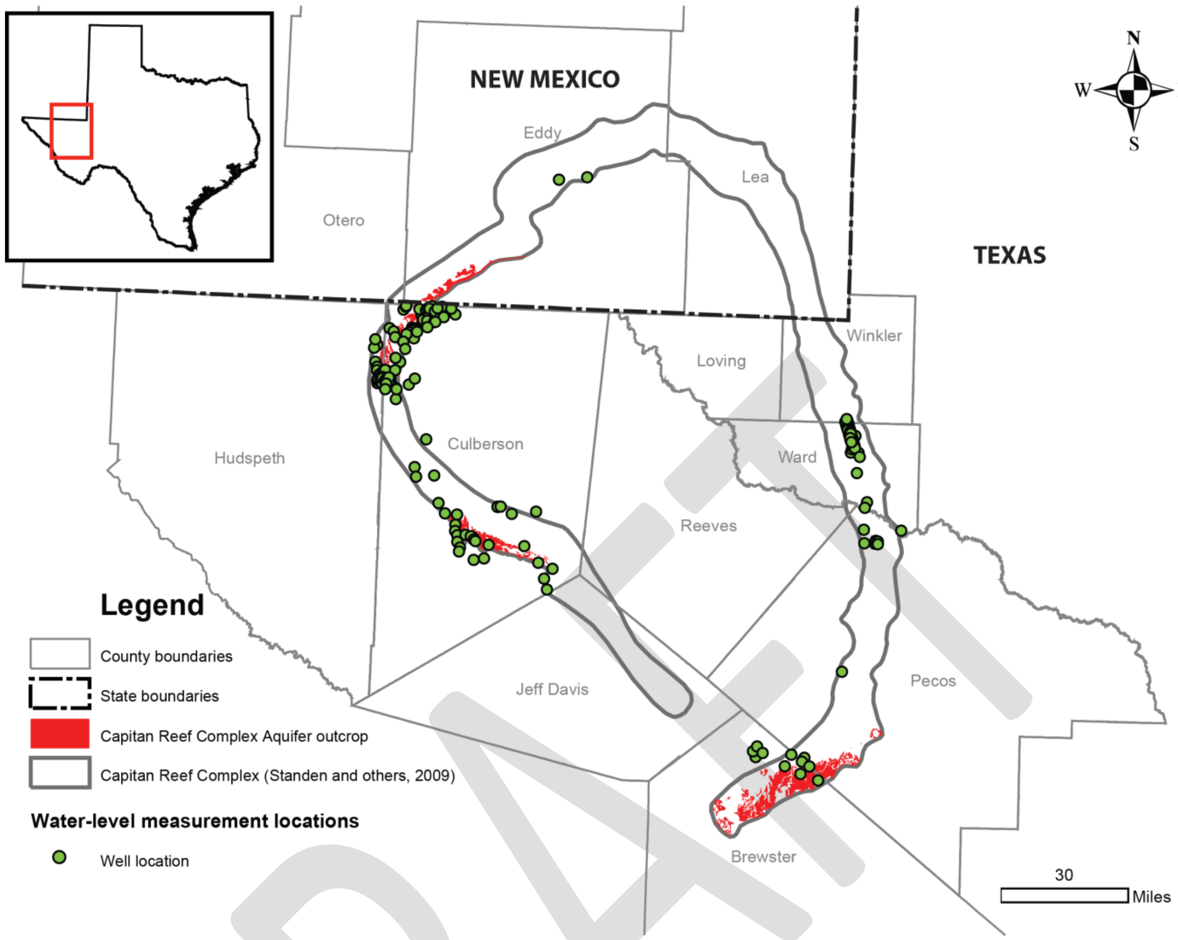


Figure 4.2.4 Water-level measurement locations for the Capitan Reef Complex Aquifer and adjacent areas (Texas Water Development Board, 2012b).

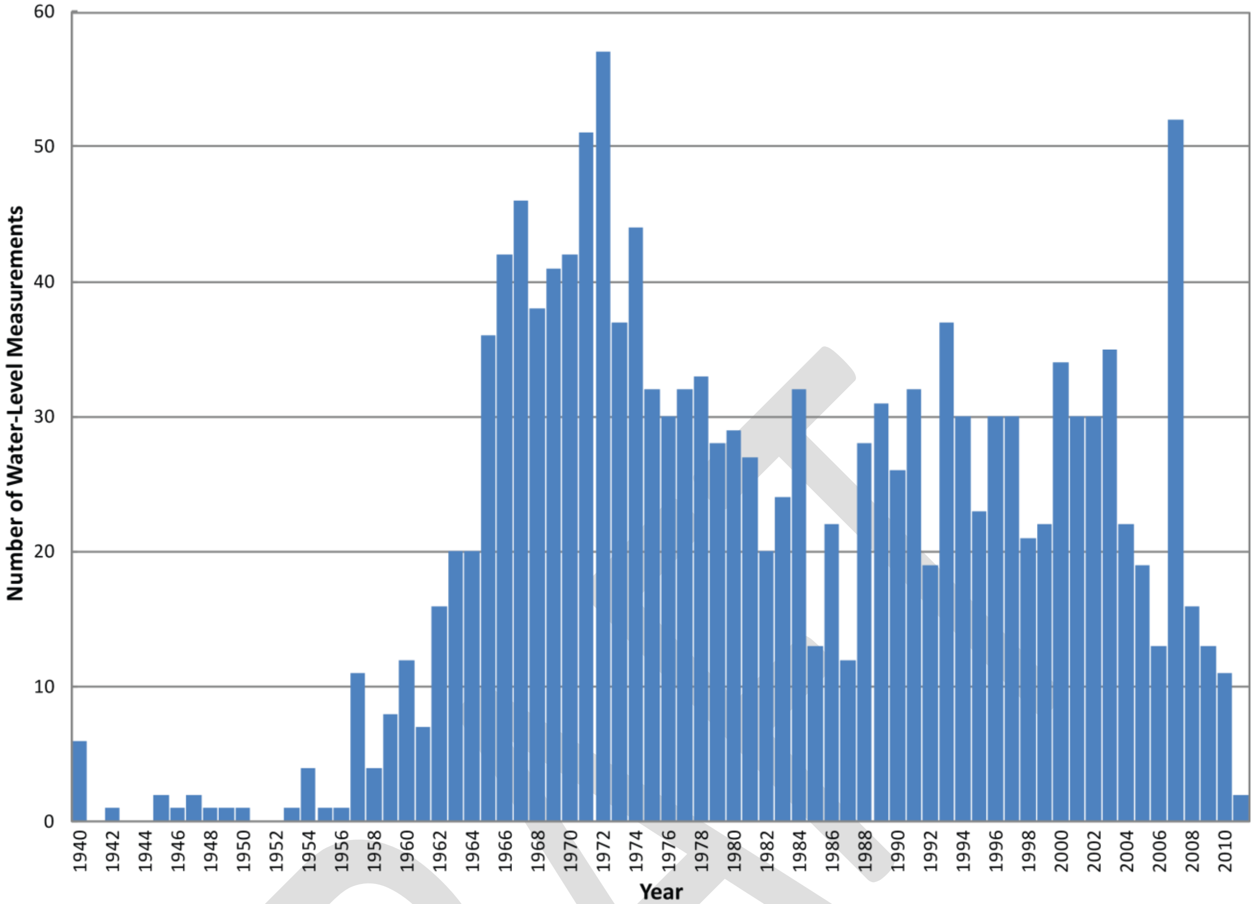


Figure 4.2.5 Temporal distribution of water-level measurements in the Capitan Reef Complex Aquifer (Texas Water Development Board, 2012b).

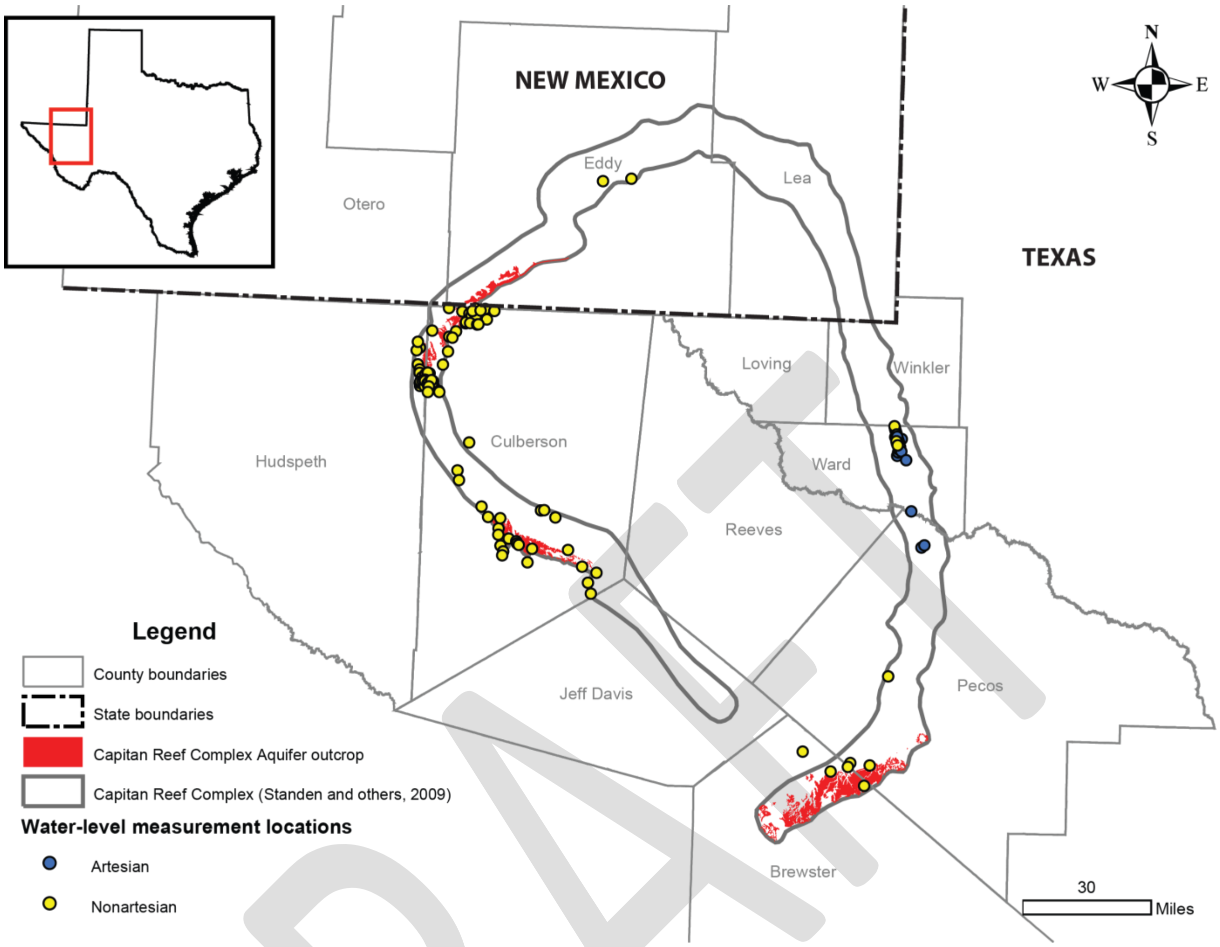


Figure 4.2.6 Locations of Capitan Reef Complex Aquifer historically artesian and non-artesian wells (Texas Water Development Board, 2012b).

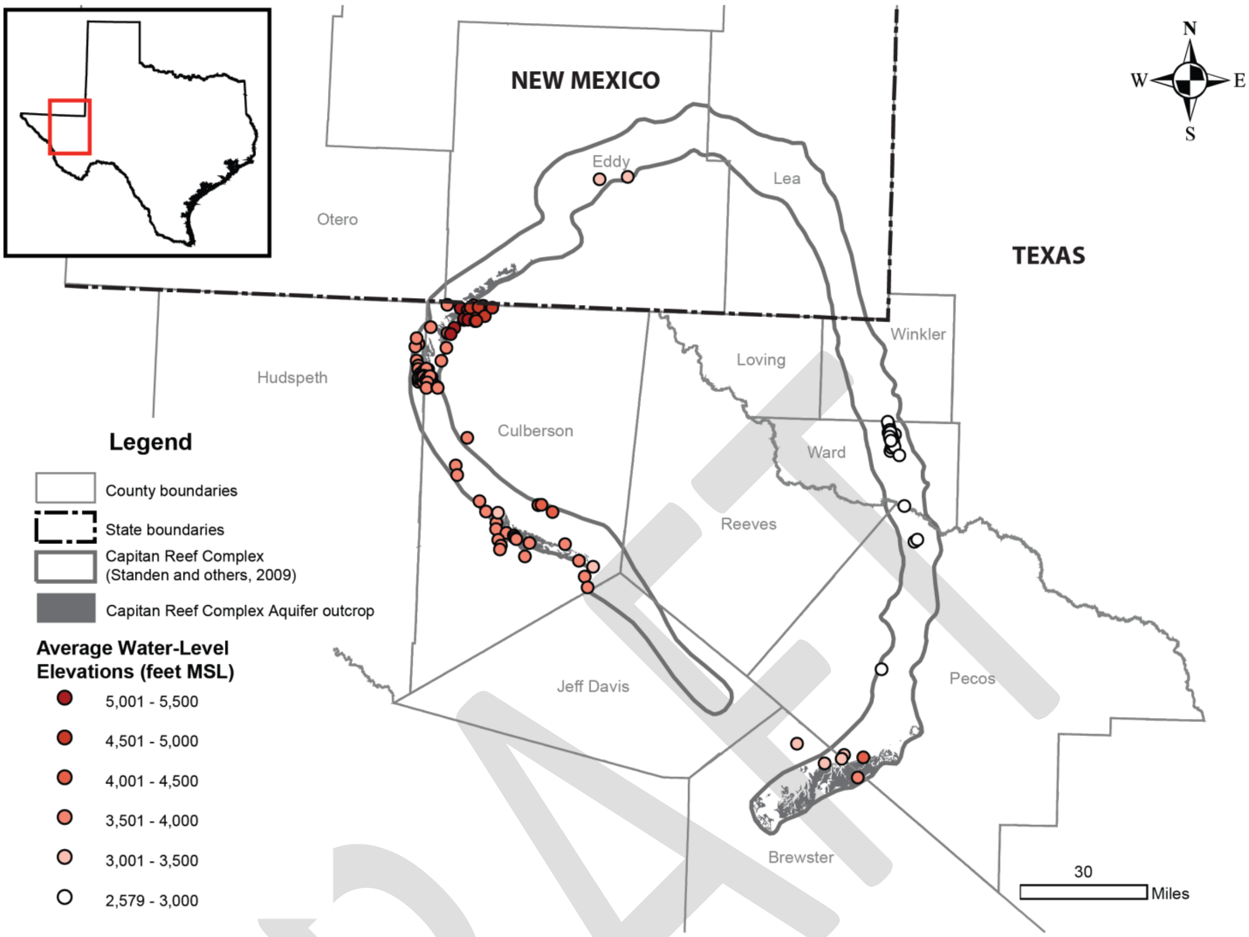


Figure 4.2.7 Average water-level elevation (in feet above mean sea level) for wells completed in the Capitan Reef Complex Aquifer (Texas Water Development Board, 2012b).

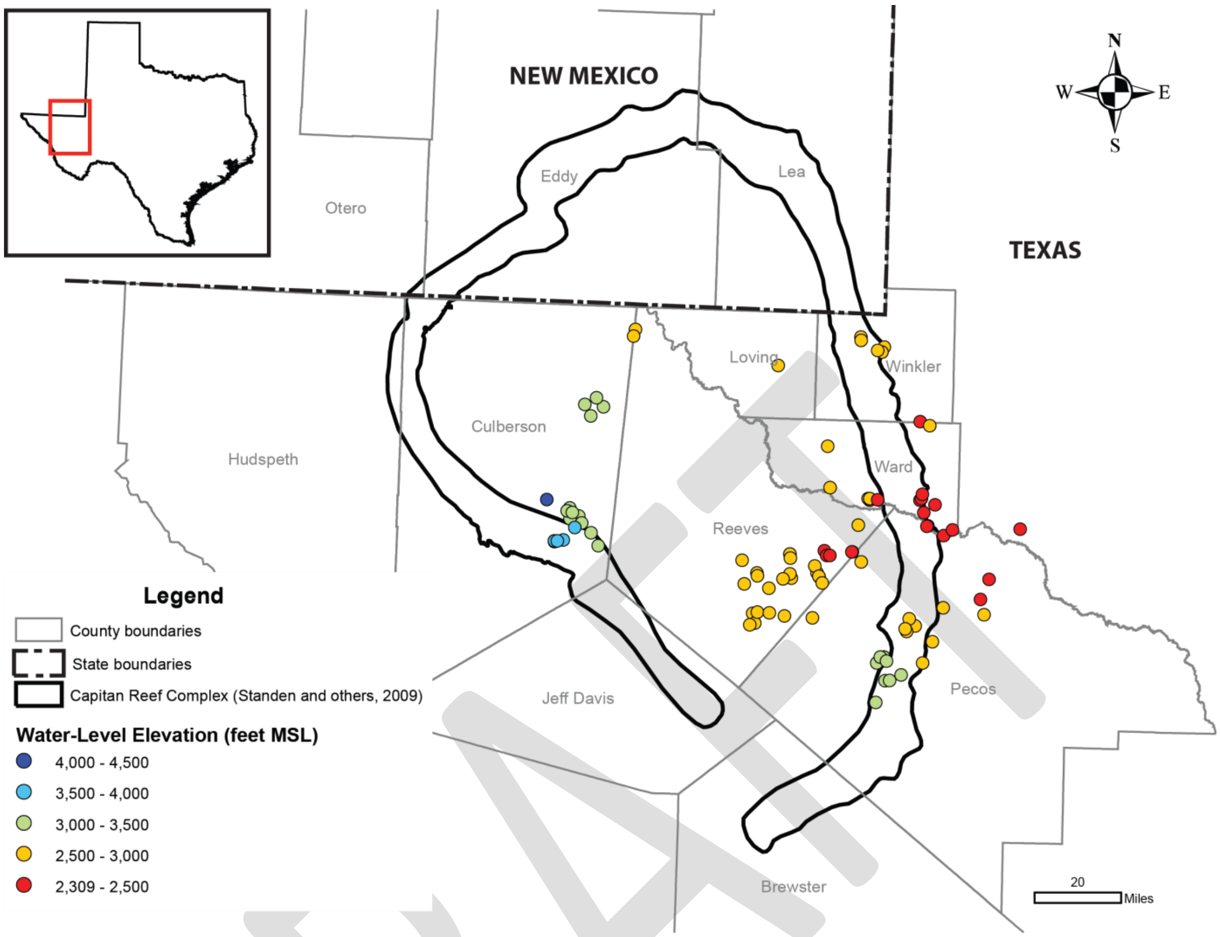


Figure 4.2.8 Average water-level elevation (in feet above mean sea level) for wells completed in the Rustler Aquifer (Texas Water Development Board, 2012b).

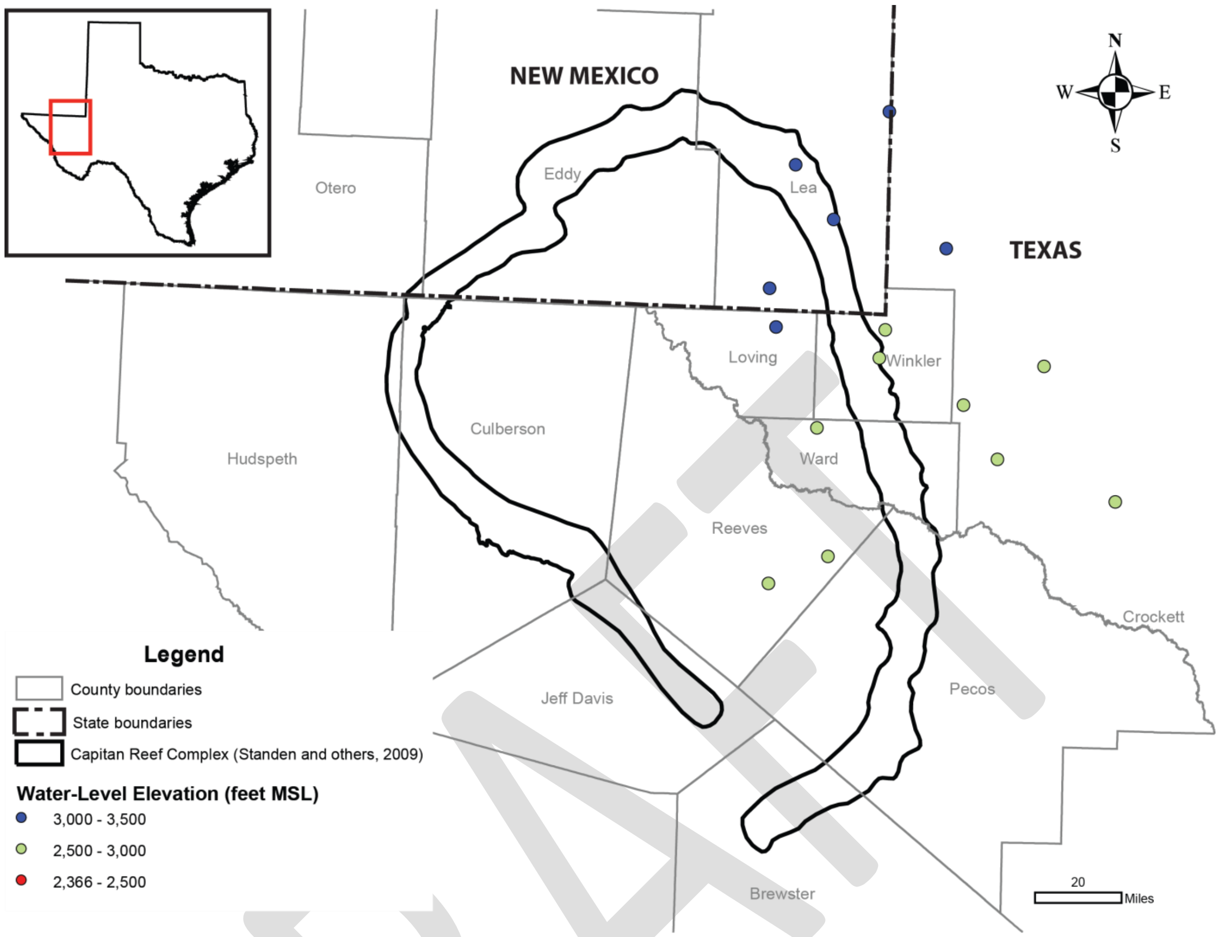


Figure 4.2.9 Average water-level elevation (in feet above mean sea level) for wells completed in the Dockum Aquifer (Texas Water Development Board, 2012b).

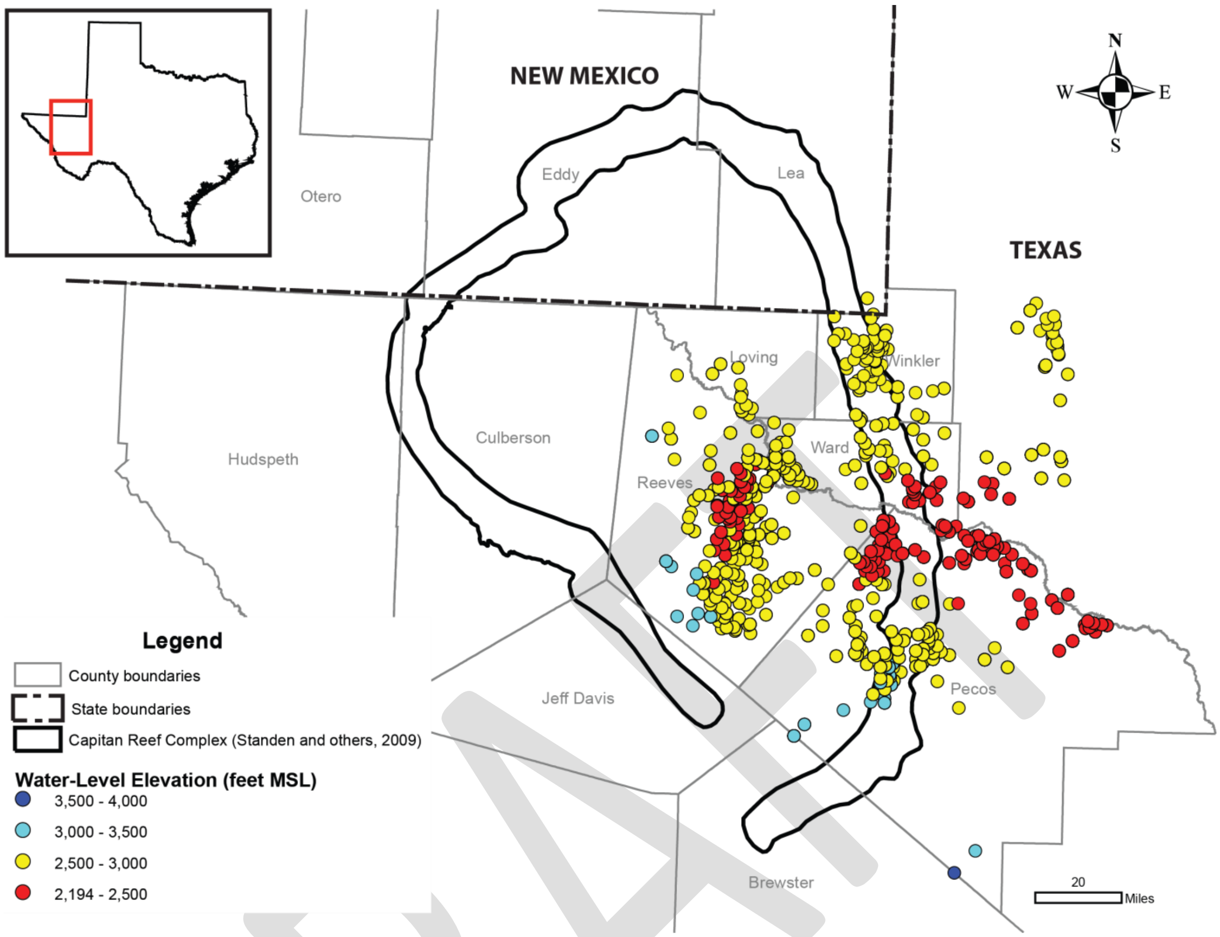


Figure 4.2.10 Average water-level elevation (in feet above mean sea level) for wells completed in the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Ewing and others, 2012; Texas Water Development Board, 2012b).

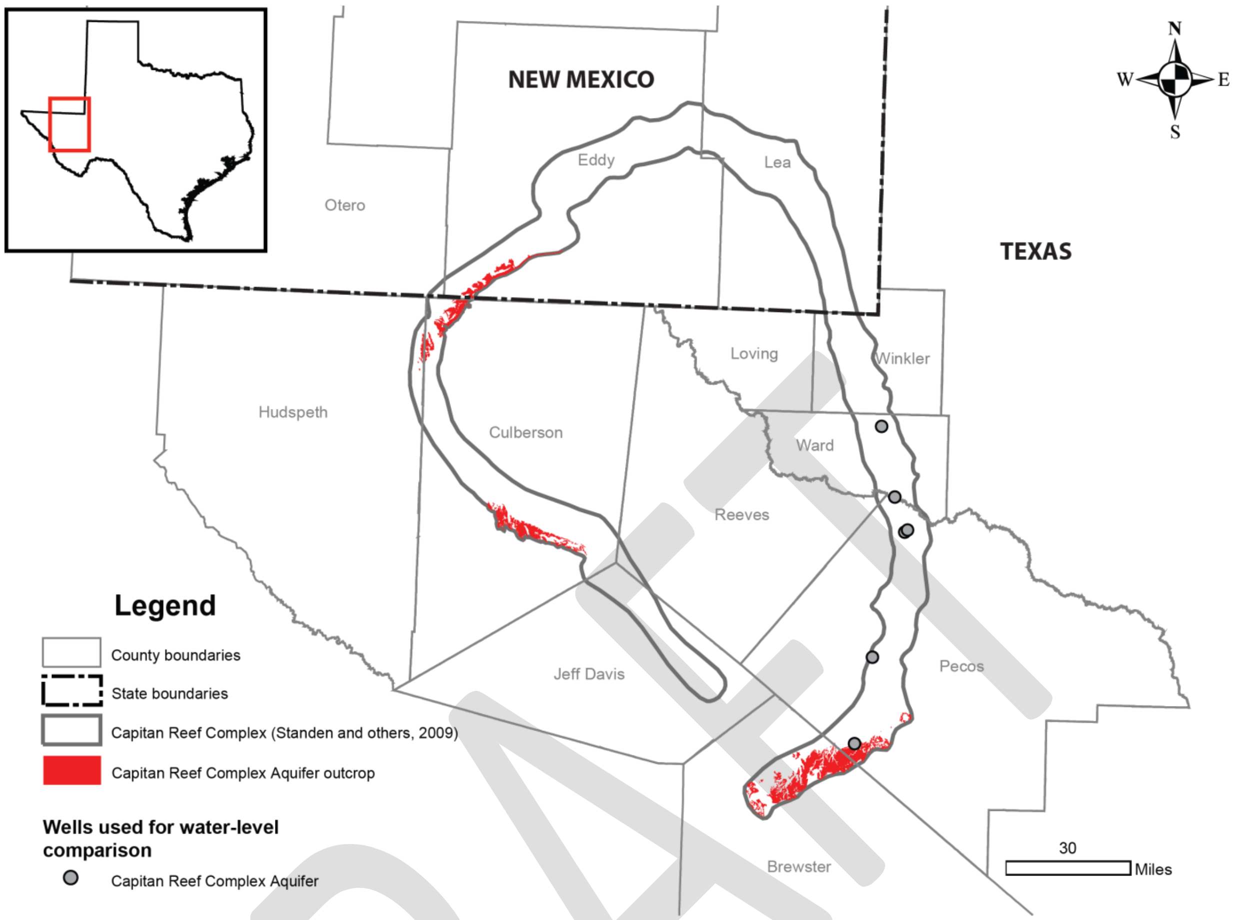
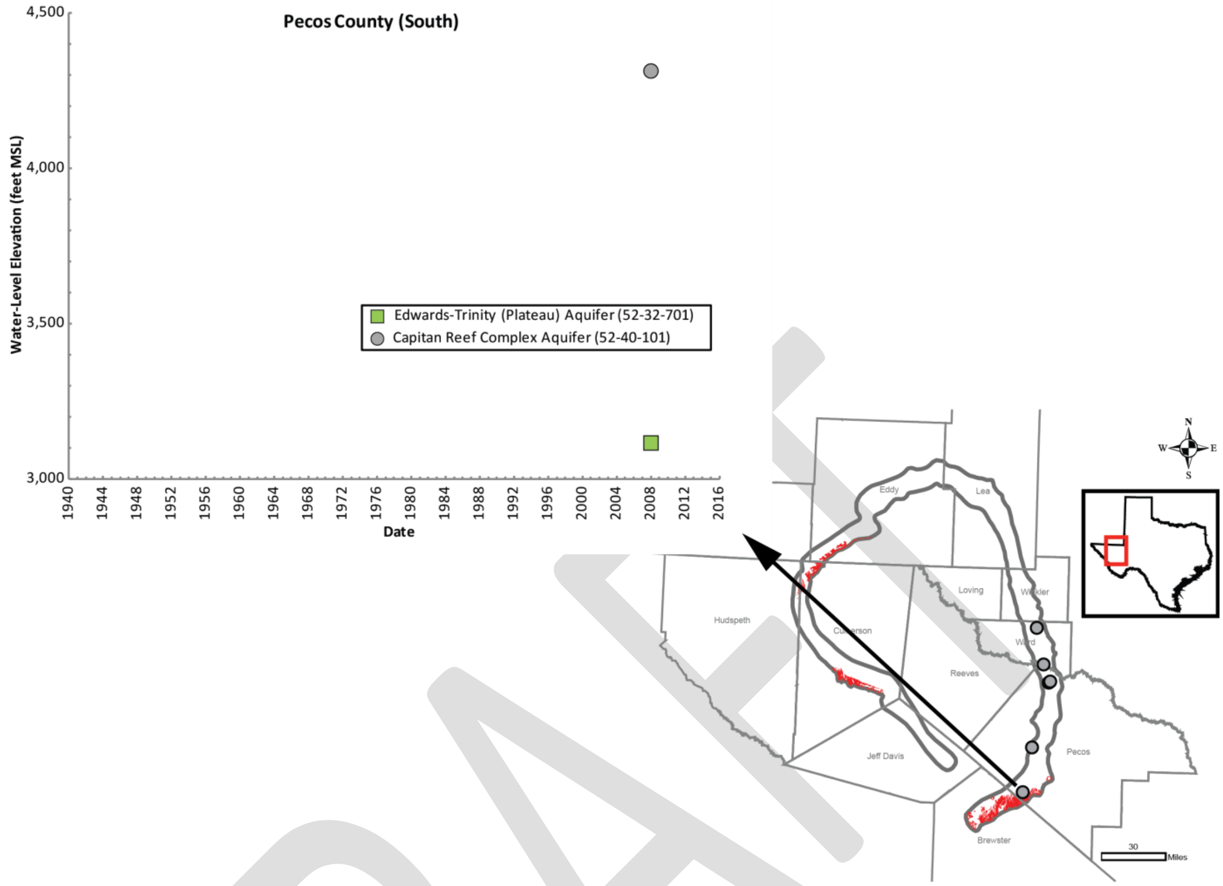
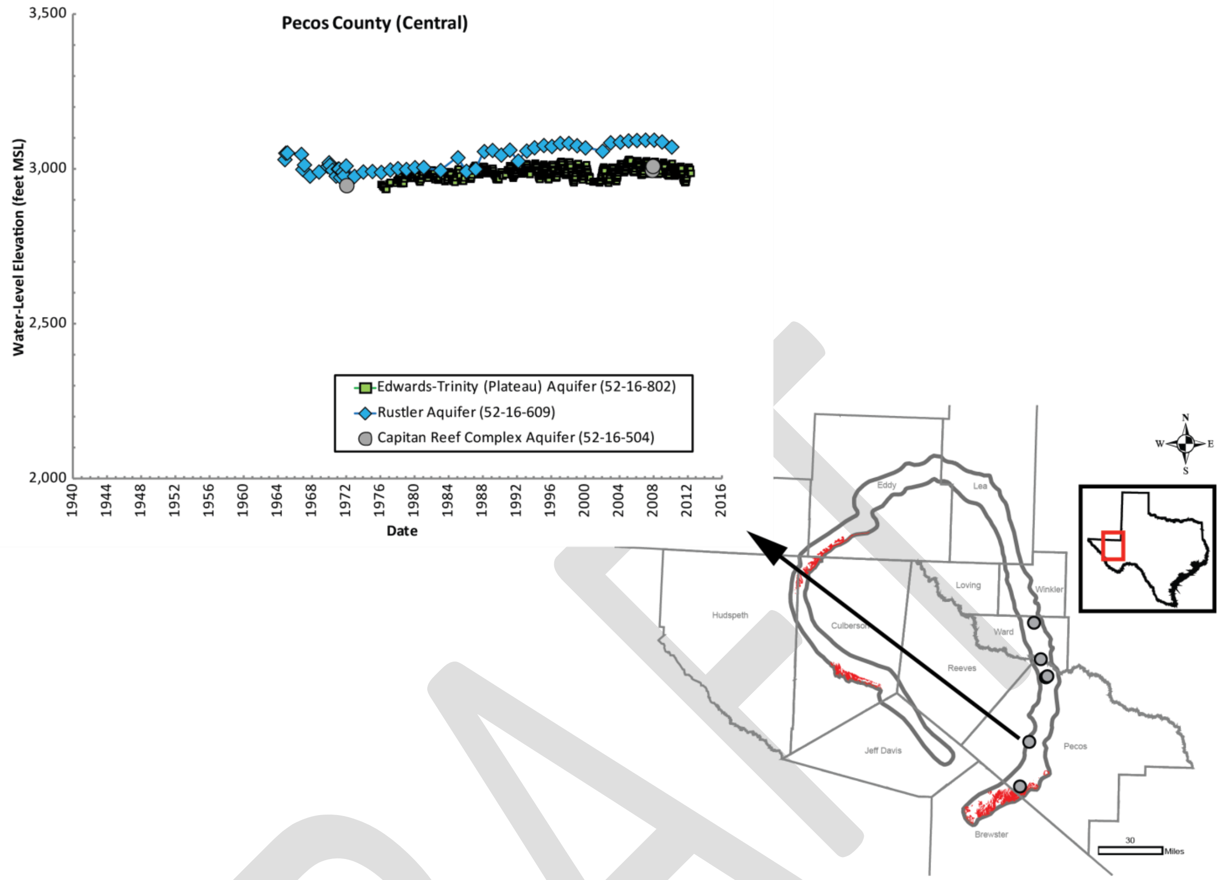


Figure 4.2.11 Locations of wells used for comparing water-level elevations between aquifers (Texas Water Development Board, 2012b).



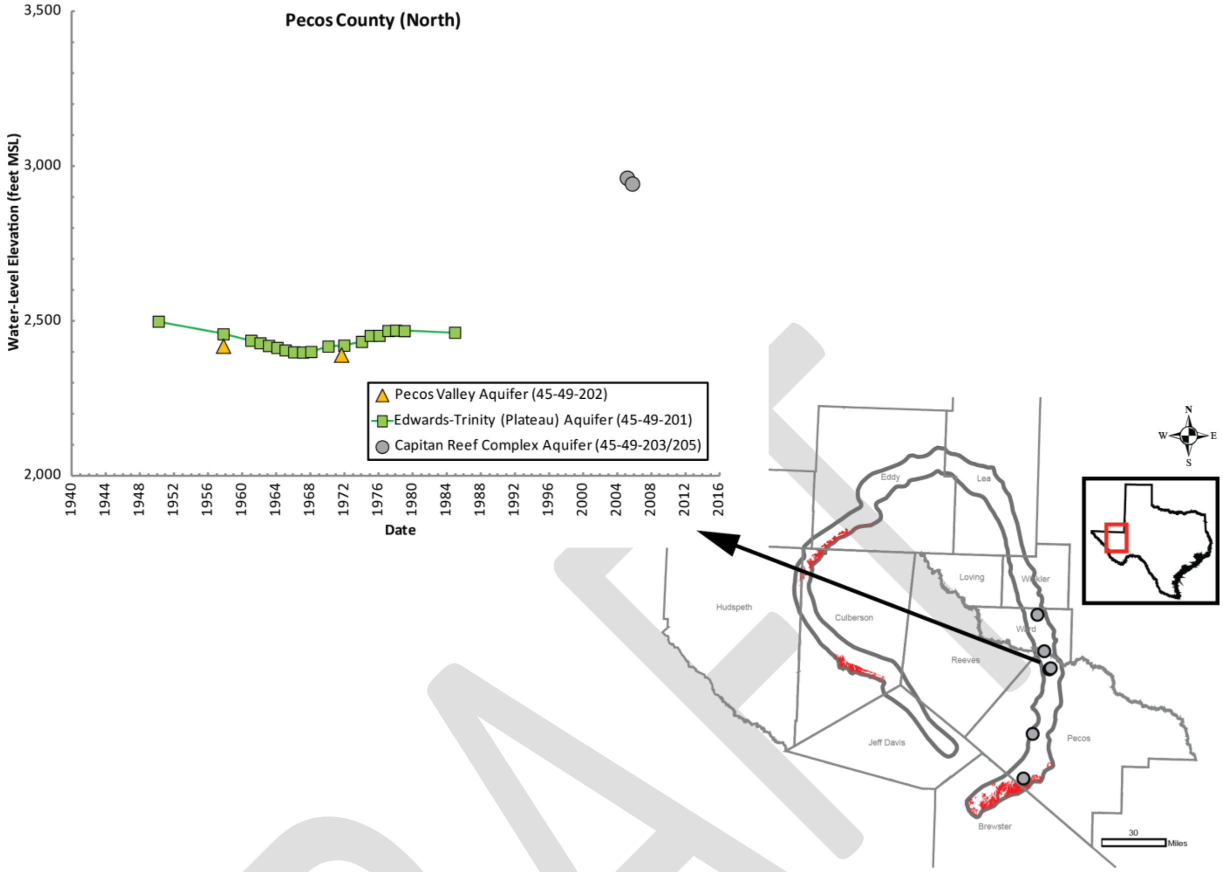
(a)

Figure 4.2.12 Comparison of water-level elevations (in feet above mean sea level) in the Capitan Reef Complex and overlying Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers (Texas Water Development Board, 2012b).



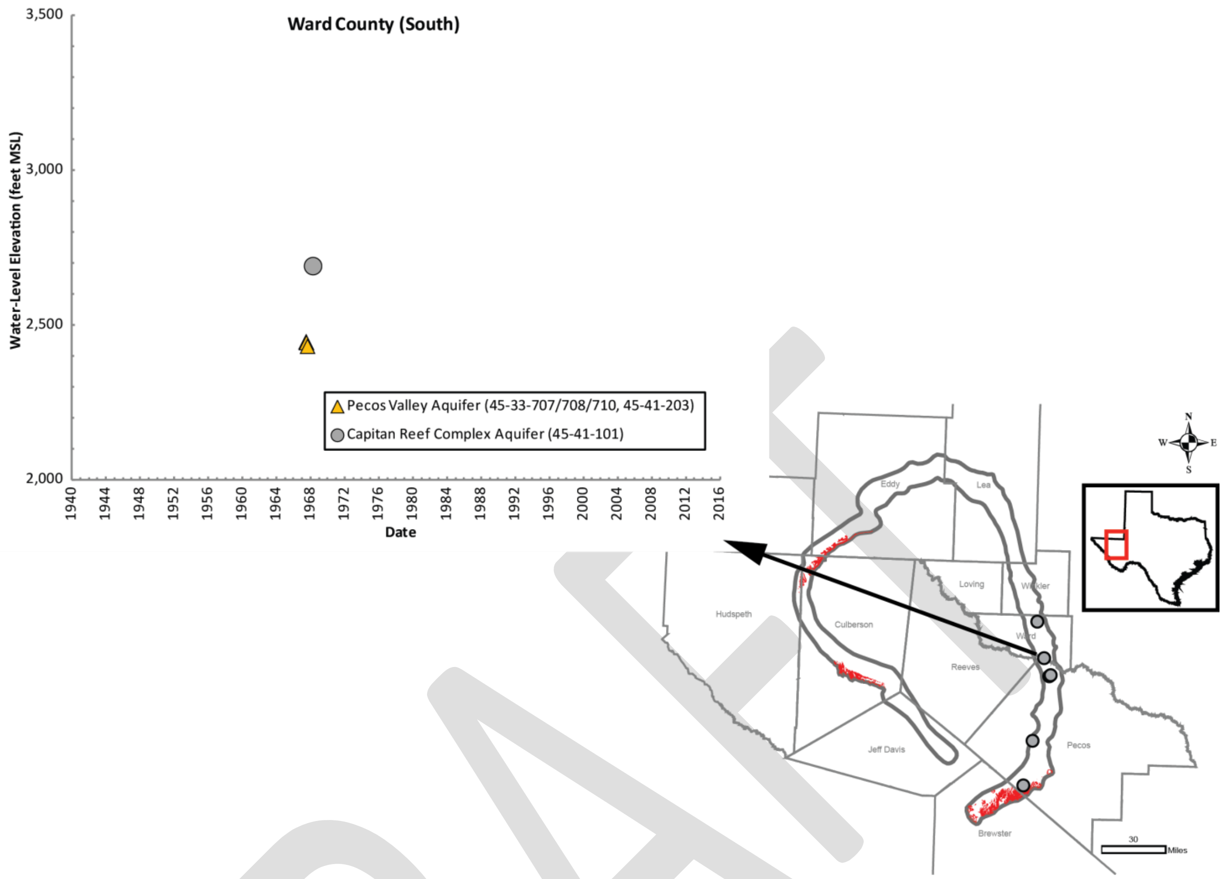
(b)

Figure 4.2.12 (continued)



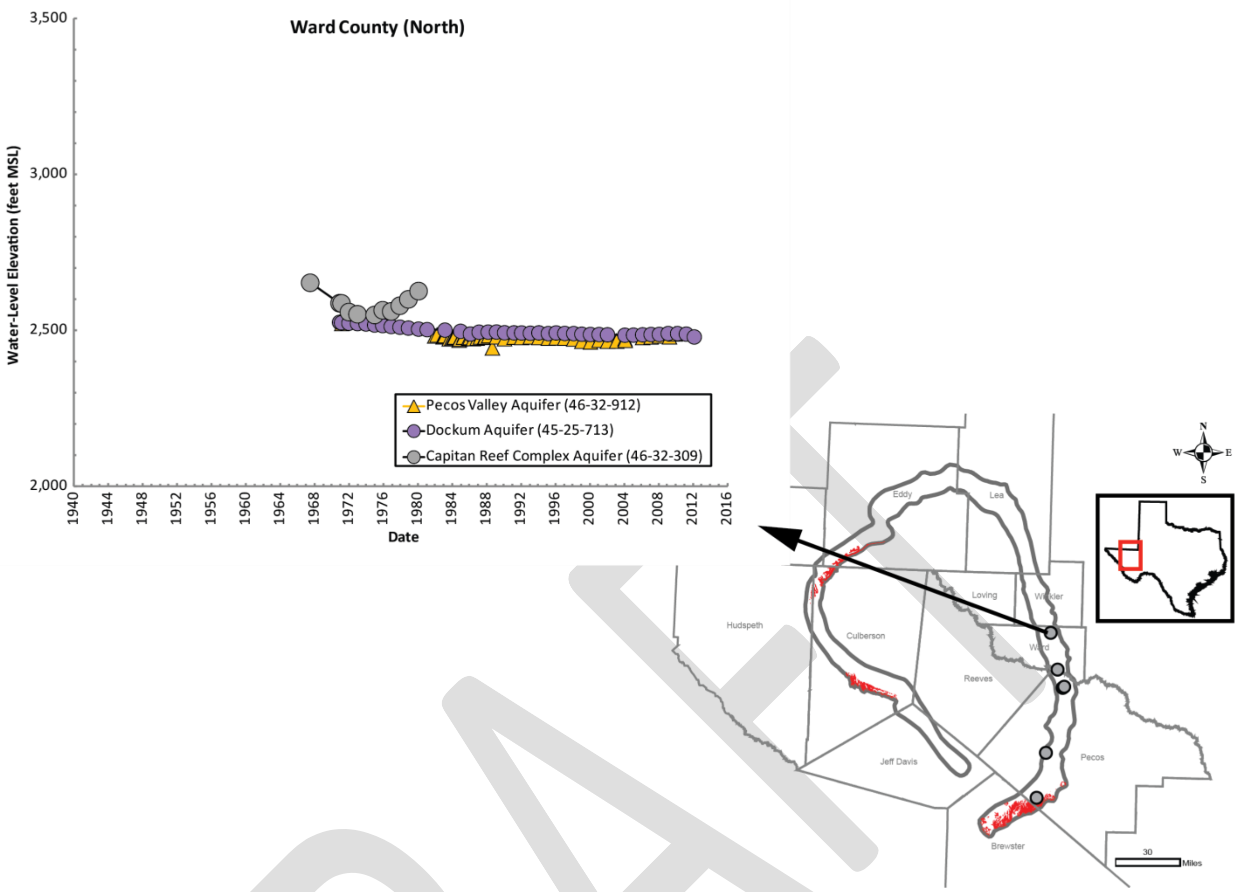
(c)

Figure 4.2.12 (continued)



(d)

Figure 4.2.12 (continued)



(e)

Figure 4.2.12 (continued)

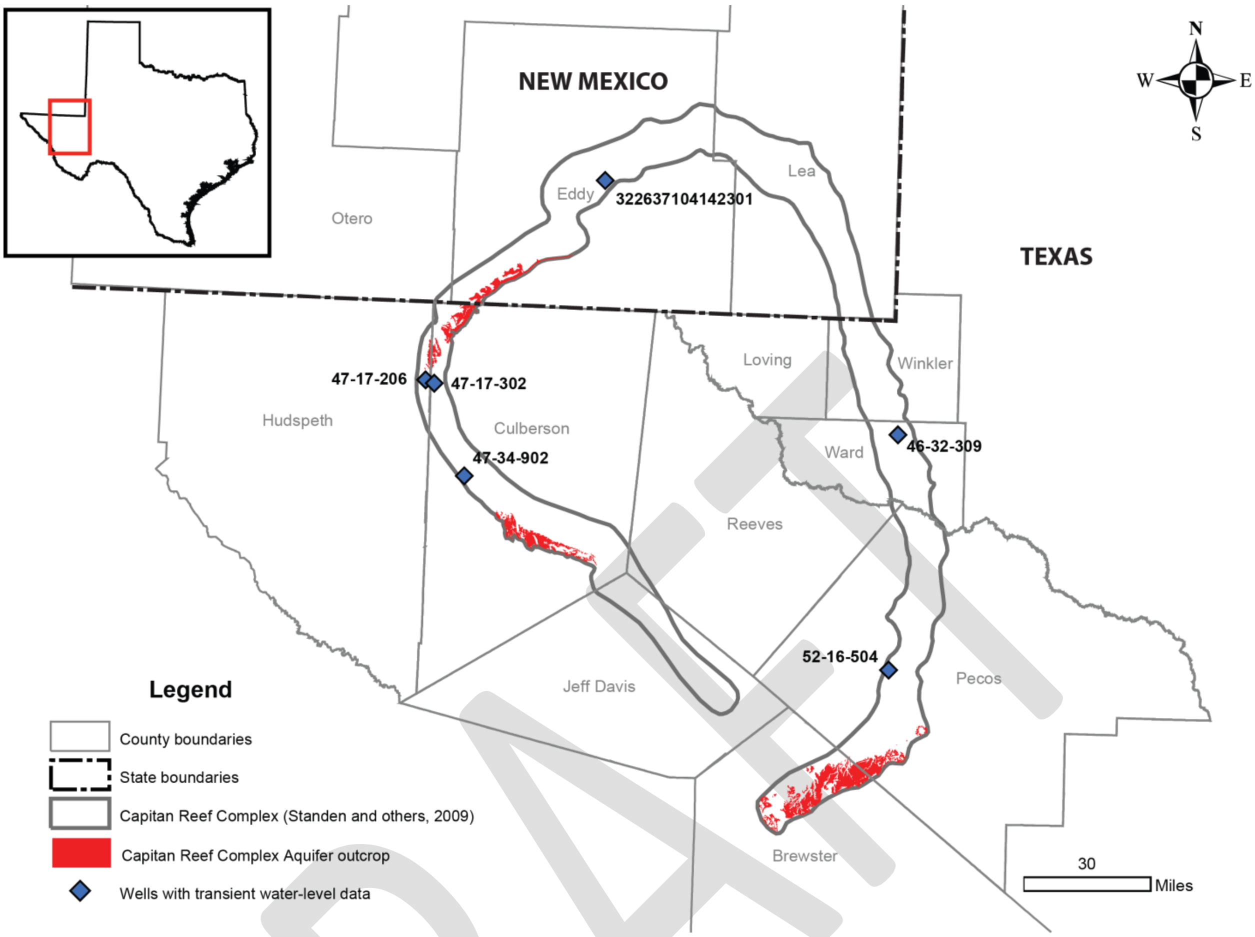


Figure 4.2.13 Locations of selected Capitan Reef Complex Aquifer wells with transient water-level data (Texas Water Development Board, 2012b; United States Geological Survey, 2012a).

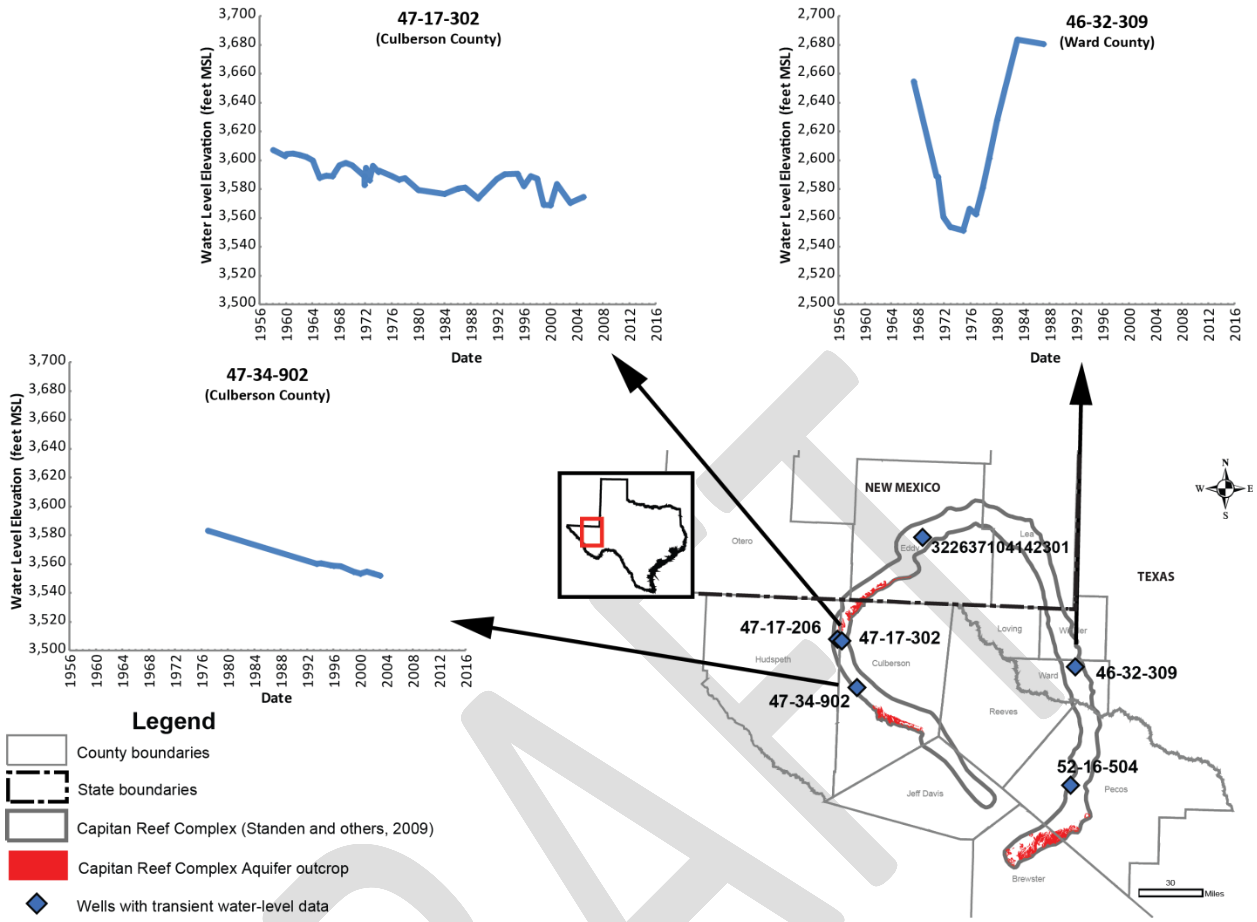


Figure 4.2.14 Hydrographs of transient water-level data (in feet above mean sea level) for Capitan Reef Complex Aquifer wells in Culberson and Ward counties (Texas Water Development Board, 2012b).

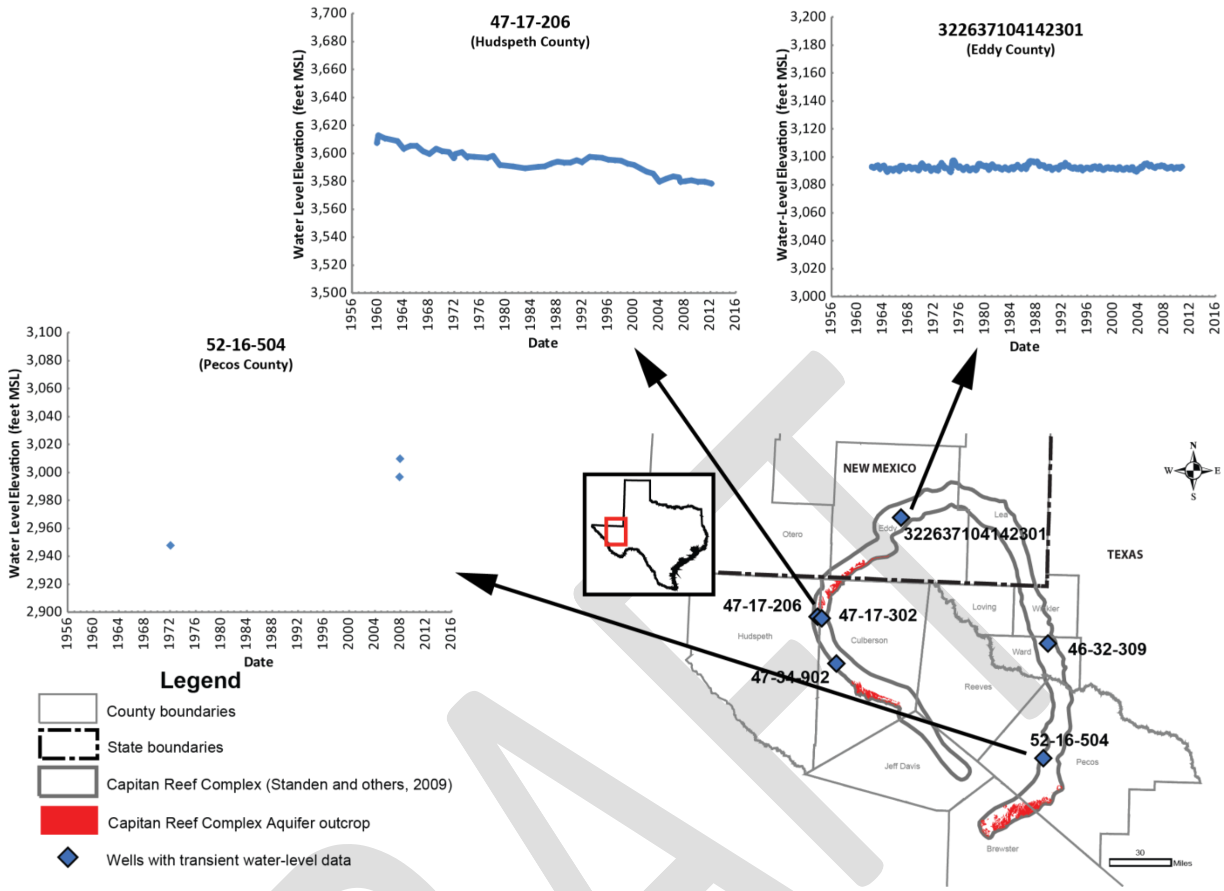


Figure 4.2.15 Hydrographs of transient water-level data (in feet above mean sea level) for Capitan Reef Complex Aquifer wells in Hudspeth and Pecos counties in Texas and Eddy County in New Mexico (Texas Water Development Board, 2012b; United States Geological Survey, 2012a).

4.3 Recharge

Recharge is defined as the processes involved in the addition of water to the water table (Jackson, 1997). Potential sources for recharge include infiltration of precipitation and stream water, and irrigation return-flow.

During a rainfall event, some of the precipitation: (1) runs off through streams, (2) is taken up through evapotranspiration, and (3) the remainder—if any—infiltrates into the soil and recharges the underlying aquifer. The potential for the occurrence of recharge to the Capitan Reef Complex Aquifer is greater where it is exposed at land surface (see Figure 4.3.1) compared to areas where infiltrating water must pass through overlying units. Faults potentially facilitate recharge both where the Capitan Reef Complex Aquifer crops out and where it is confined by overlying aquifers or aquitards—rocks that do not transmit useable amounts of water and thus do not meet the criteria to be aquifers. Recharge to the Capitan Reef Complex Aquifer is potentially topographically controlled, with higher recharge in the areas of higher elevation where the amount of precipitation is highest and the evaporative potential is least (Figures 2.1.3 and 2.1.6).

Isotopes in groundwater, such as carbon-13, carbon-14, tritium, and stable hydrogen and oxygen can be used to determine the spatial and seasonal distribution of recharge to an aquifer (See Section 4.7). The carbon-13 and carbon-14 isotopic compositions of Capitan Reef Complex Aquifer groundwater indicate recharge zones in the Guadalupe and Glass mountains but little recharge in the Apache Mountains—all areas where the aquifer crops out. The carbon-13 and carbon-14 isotopic compositions also indicate recharge associated with faults near the southern margin of the Delaware Mountains. Groundwater tritium compositions indicate that the most recent recharge to the Capitan Reef Complex Aquifer occurred near the southern margin of the Delaware Mountains. The stable oxygen and hydrogen isotopes indicate a relatively simple flow system in the eastern arm of the Capitan Reef Complex Aquifer with a single recharge zone. In the west, there is a more complex system where recharge takes place under a range of conditions.

INTERA (2013) estimated recharge to the outcrop of the Capitan Reef Complex Aquifer in the Glass Mountains of 0 to 2.69 inches per year and averaging 0.63 inches per year. There are some other studies of recharge in arid environments that have some relevance to the Capitan Reef Complex Aquifer (Hibbs and Darling, 1995; Hibbs and others, 1998; Stone and others, 2001; Beach and others, 2004; Wilson and Guan, 2004; Berger and others, 2008).However, these studies are no directly applicable to the Capitan Reef Complex Aquifer. Ewing and others (2012) estimated potential recharge to the Capitan Reef Complex Aquifer in the Glass Mountains in the range of 1,090 to 14,210 acre-feet per year during their study of the Rustler Aquifer. These estimates are based on assumed recharge factors—percentages of average annual precipitation—ranging from 0.77 percent to 10 percent. These highest recharge factors were justified by the occurrence of karst features in the Glass Mountains that have the potential to facilitate rapid infiltration of large amounts of recharge water.

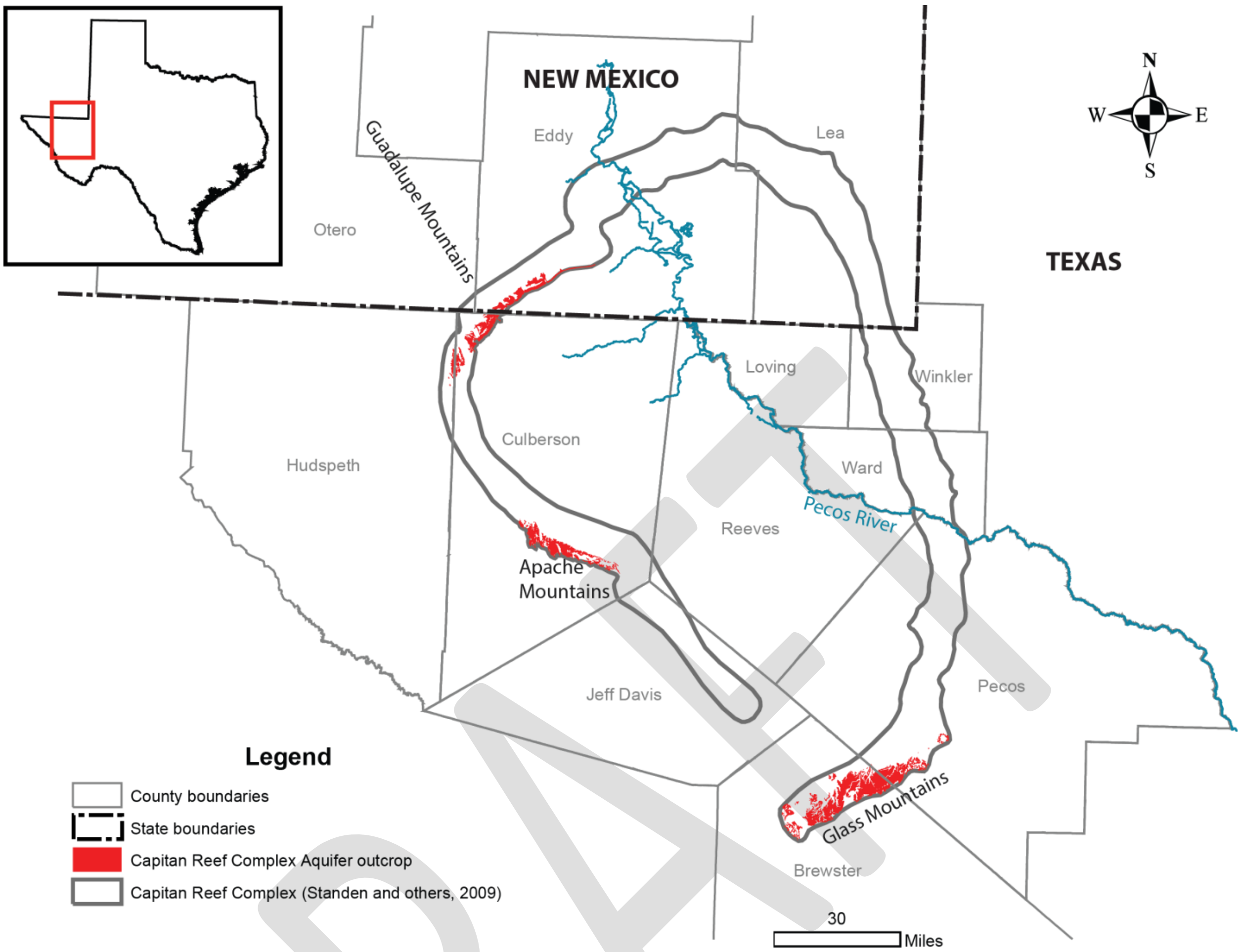


Figure 4.3.1 Capitan Reef Complex Aquifer outcrop regions where the potential for recharge is assumed to be the greatest.

4.4 Rivers, Streams, Springs, and Lakes

Interaction between groundwater and surface water occurs primarily where surface water bodies—rivers and streams, springs, and lakes—intersect with aquifer outcrops. These interactions result in flow between the aquifer and surface water body. The direction of flow depends on the relative groundwater and surface water levels with water flowing from relatively high to relatively low water levels.

4.4.1 Rivers and Streams

Interaction between groundwater and rivers and streams depends on the relative elevations of the water table and the stream stage. In losing streams, the water table is below the elevation of the stream stage, and the gradient causes water to flow from the stream to the aquifer. In gaining streams, the water table is above the elevation of the stream stage and consequently water flows from the aquifer into the stream.

No existing studies were found to describe river gain/loss in the Capitan Reef Complex Aquifer outcrop. This is not surprising because there are very few perennial water bodies in the study area (Figure 2.0.4). The unproductive search of existing studies included a review of gain/loss studies in Texas completed by Slade and others (2002). Determination of streamflow gain or loss in the Pecos River where it crosses the Capitan Reef Complex Aquifer is difficult because of the presence of a reservoir—Lake Avalon—that disruption natural flow through the river. Comparison of streamflow at upstream and downstream locations on the Capitan Reef Complex Aquifer outcrop—Stations 08401500 and 08405200, respectively—suggest mostly declining streamflow across the outcrop (Figure 4.4.1). This contradicts findings by Hiss (1980) who reported aquifer discharge along the river. The declining streamflow may be explained by increasing storage in Lake Avalon and the fact that due to the presence of the reservoir located between the two gaging stations, the Pecos River does not flow naturally (also see Section 4.4.3).

4.4.2 Springs

Springs are locations where the water table intersects the ground surface. Spring data for the Capitan Reef Complex Aquifer were found in the Texas Water Development Board groundwater database (TWDB, 2012b), a database of Texas springs compiled by the United States Geological Survey (Heitmuller and Reece, 2003), and a report on the springs of Texas by Brune (2002). Only one spring identified as discharging from the Capitan Reef Complex Aquifer was located from the three sources—Frijoles Spring—located in the Guadalupe Mountains (Figure 5.5.2). A second spring—Carlsbad Springs—is located in New Mexico. Discharge from Carlsbad Springs to the Pecos River is reported to include groundwater discharge from the Capitan Reef Complex Aquifer in addition to groundwater from the overlying Artesia Group (Bjorklund, 1958; Thomas, 1963; Texas Department of Water Resources, 1978).

There is very little spring discharge data available for springs discharging from the Capitan Reef Complex Aquifer. Spring discharge from Frijoles Spring was reported as less than 2 gallons per minute (TWDB, 2012b). It should be noted that Carlsbad Springs receives water from multiple sources in addition to the Capitan Reef Complex Aquifer (Bjorklund, 1958; Cox, 1967; Texas Department of Water Resources, 1978). These sources include Lake Avalon, return-flow from nearby irrigated farmland and discharge from overlying stratigraphic units. Reported discharge rates from Carlsbad Springs range from 30 cubic feet per second to 100 cubic feet per second (Bjorklund, 1958).

4.4.3 Lakes and Reservoirs

Typically, interaction between an aquifer and a lake or reservoir is restricted to the outcrop area of an aquifer where the lake or reservoir lies directly on the aquifer. There are no natural lakes or reservoirs in the outcrop of the Capitan Reef Complex Aquifer. However, there is thought to be interaction between the Capitan Reef Complex Aquifer and Lake Avalon, which is located on the Pecos River overlying the Capitan Reef Complex Aquifer (Figure 5.5.3). Bjorklund (1958) and Cox (1967) discuss the interaction of Lake Avalon, the Capitan Reef Complex Aquifer, and Carlsbad Springs. They found that water seeps from Lake Avalon, recharging the underlying

Capitan Reef Complex Aquifer and rapidly discharges back into the Pecos River downstream through the Carlsbad Springs. Bjorklund (1958) suggested that the net effect of seepage from Lake Avalon on discharge at Carlsbad Springs lags by one to three months. These effects are superimposed upon effects associated with fluctuations of the water levels in the Capitan Reef Complex Aquifer.

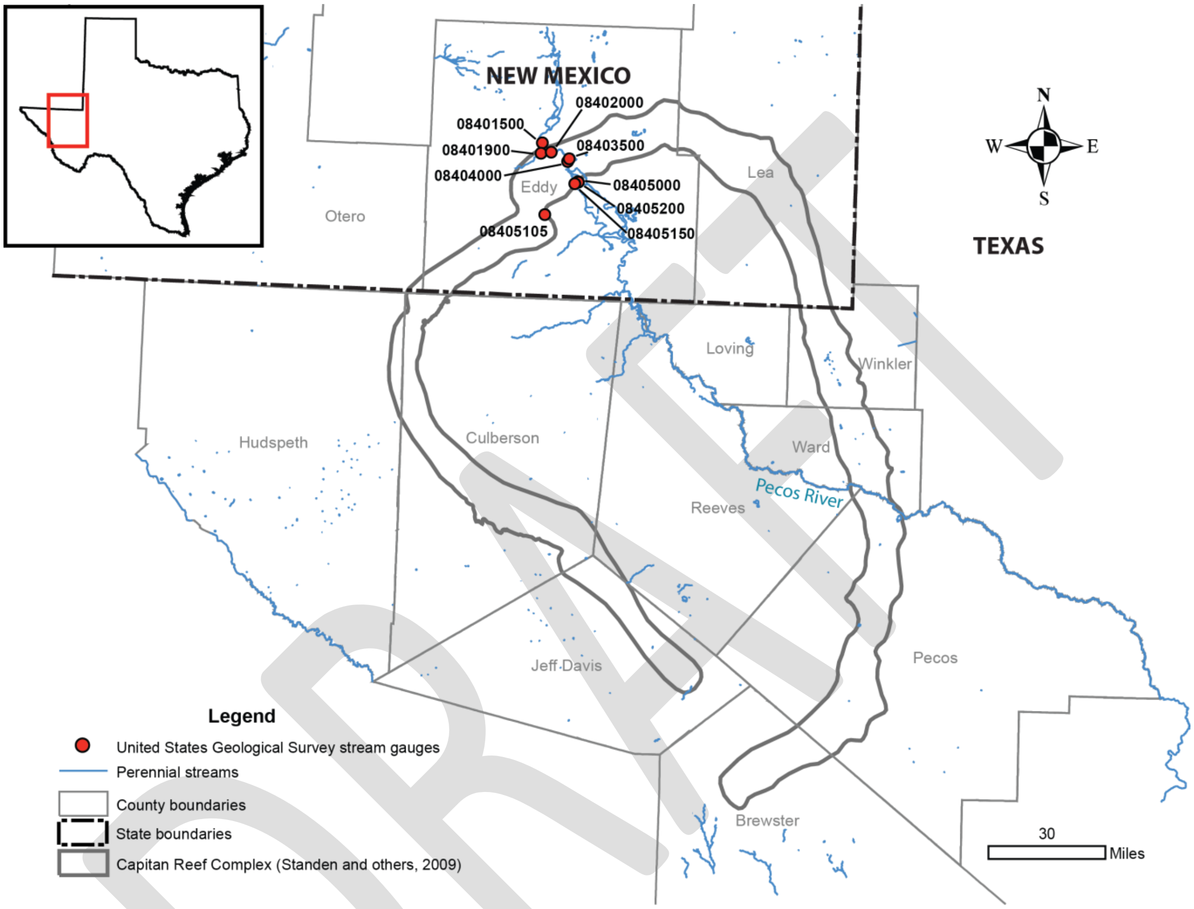


Figure 4.4.1 Locations of stream gauges along the Pecos River (United States Geological Survey, 2012b.

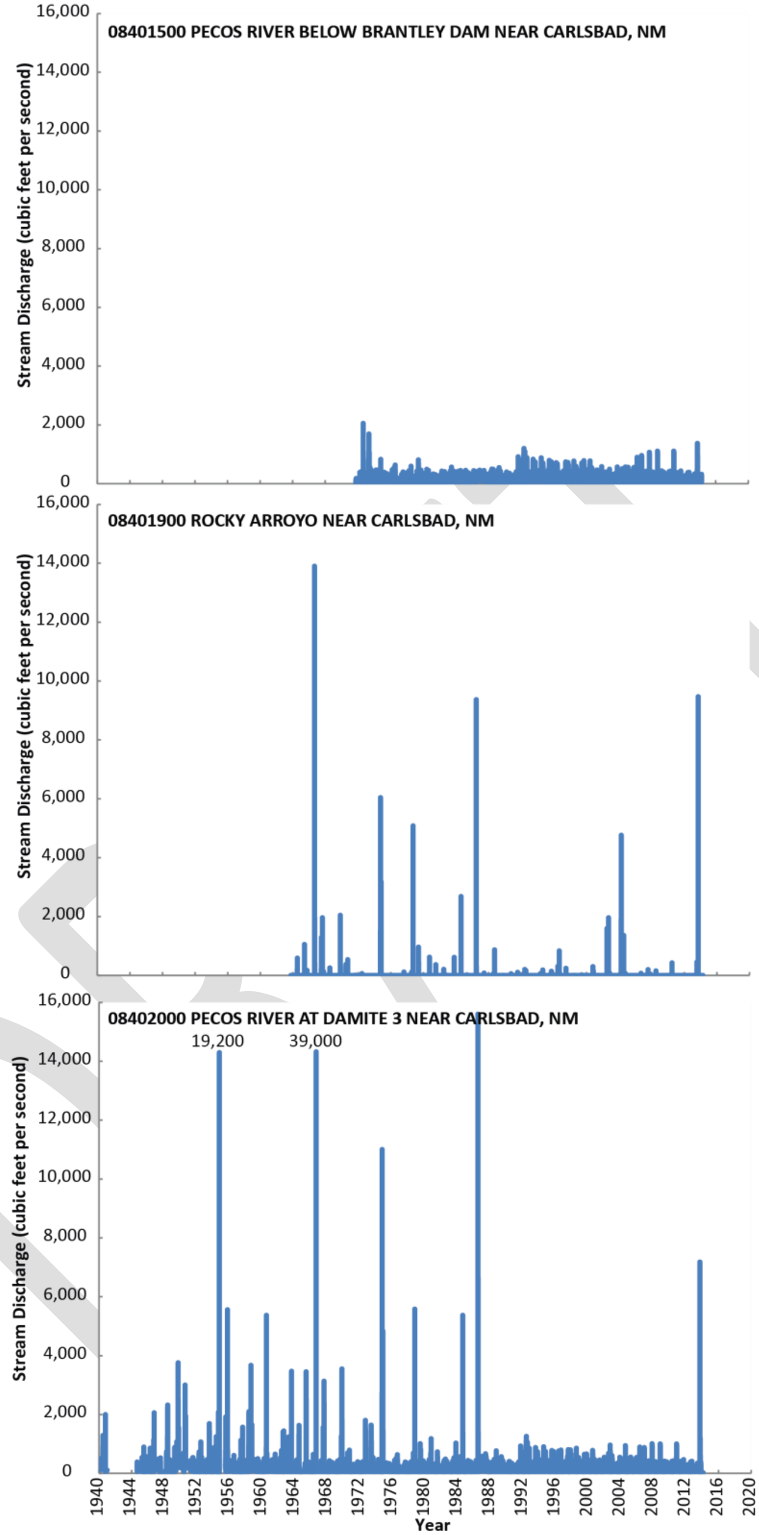


Figure 4.4.1 (continued).

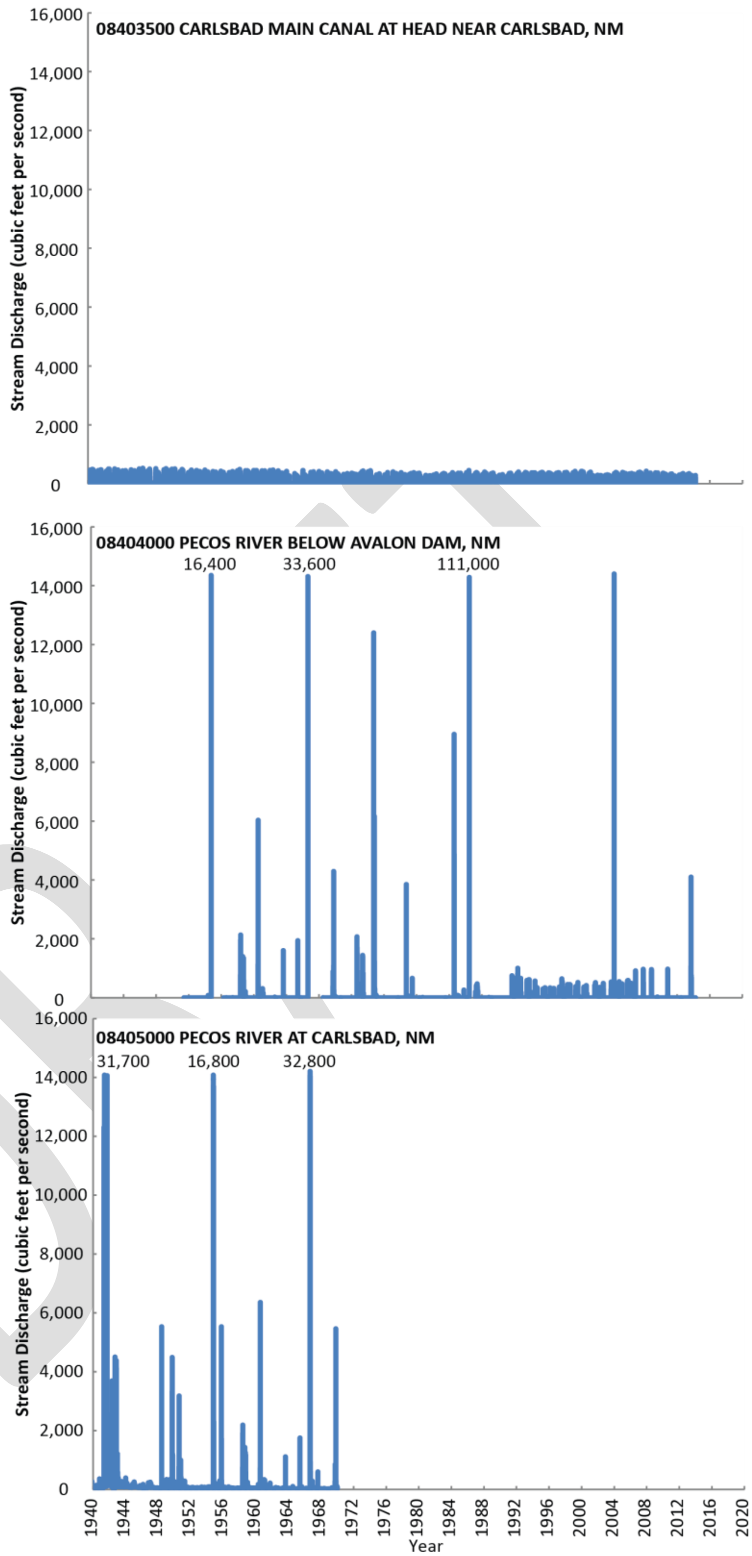


Figure 4.4.1 (continued).

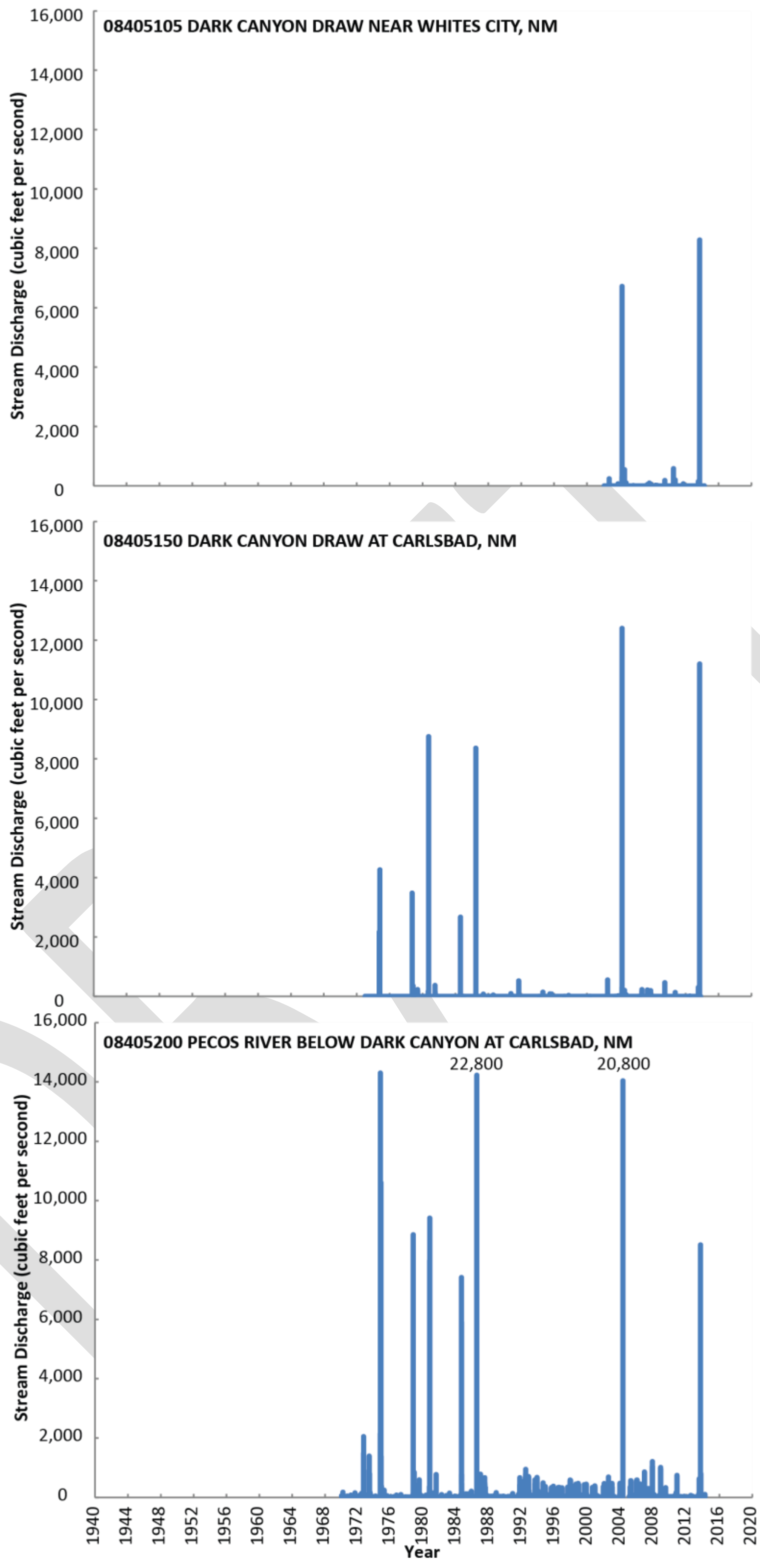


Figure 4.4.1 (continued).

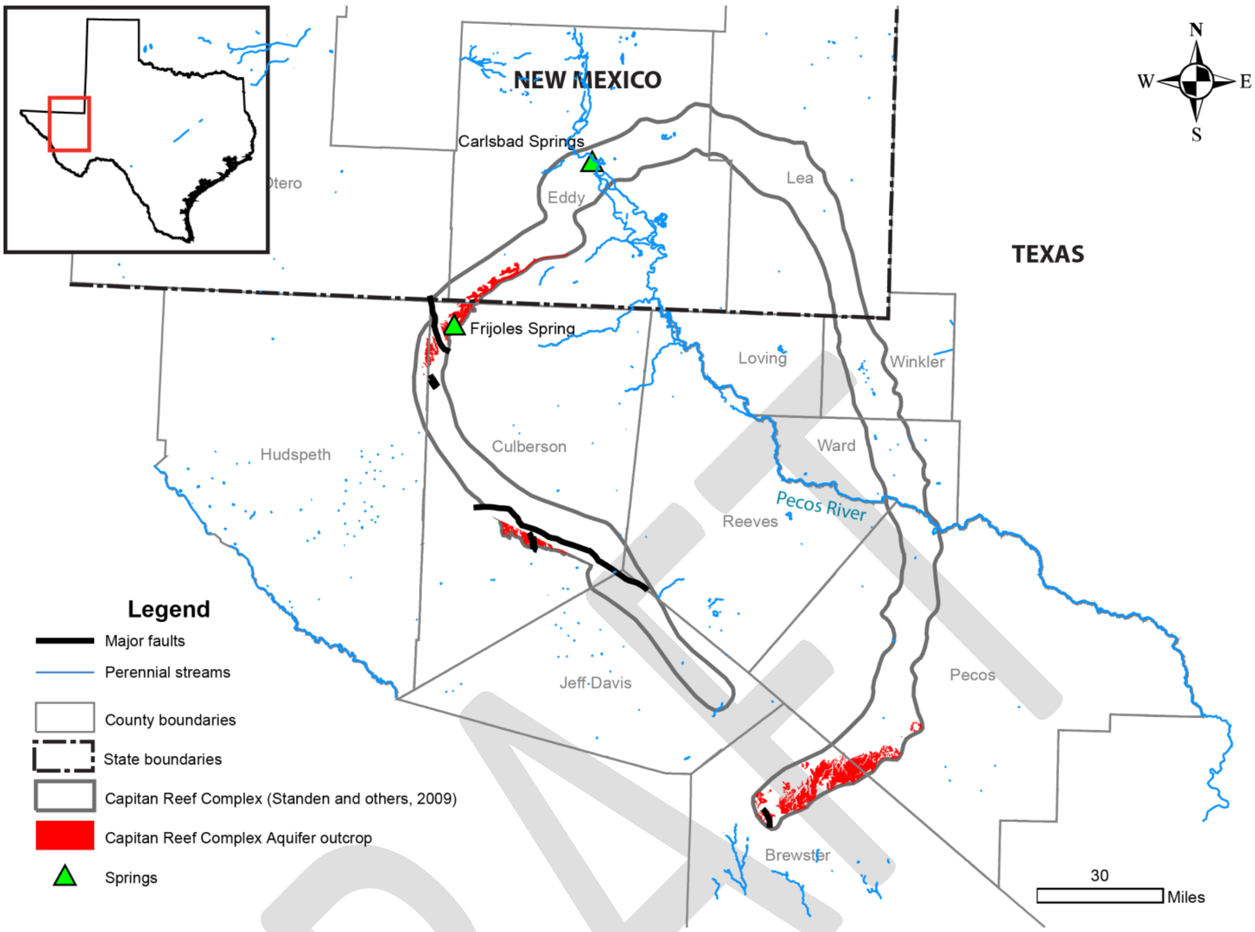


Figure 4.4.2 Locations of springs flowing from the Capitan Reef Complex Aquifer (Texas Department of Water Resources, 1978; Heitmuller and Reece, 2003).

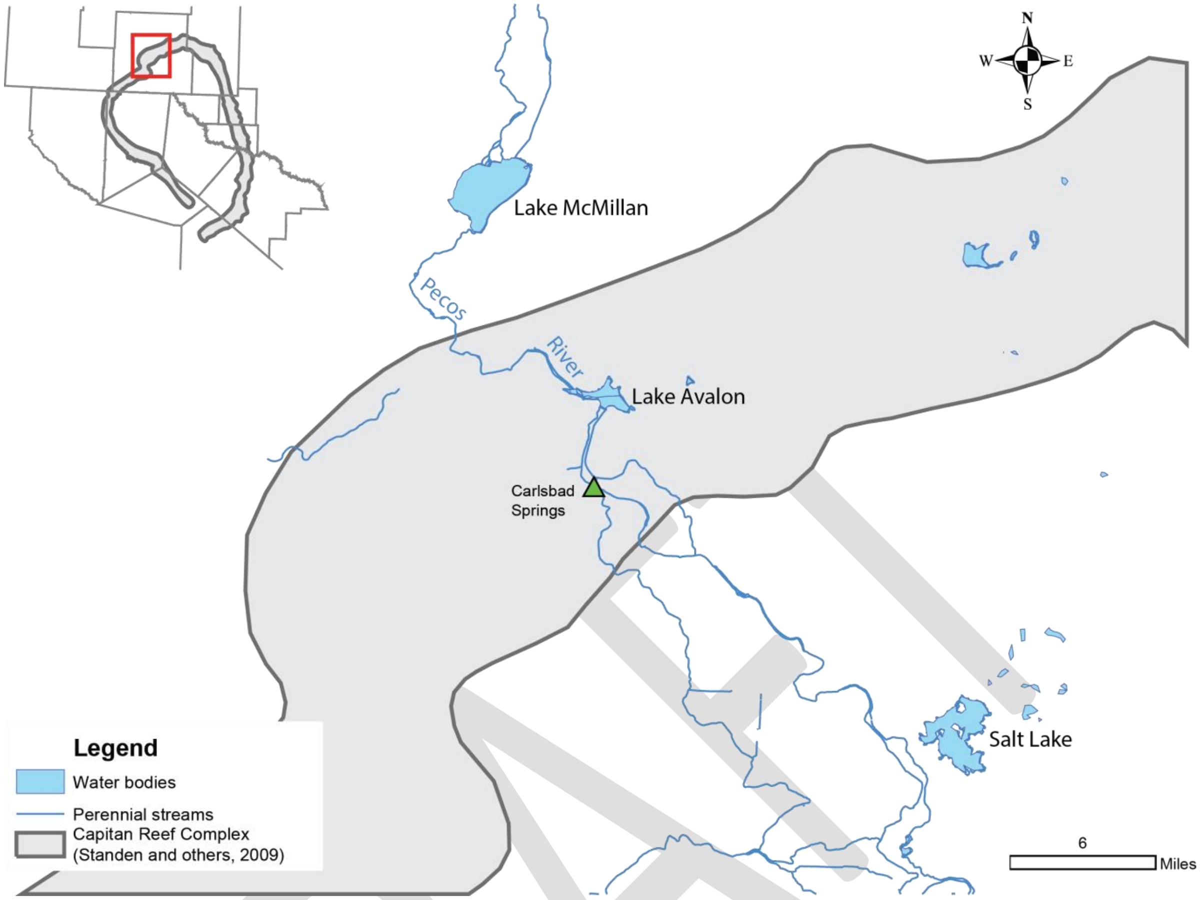


Figure 4.4.3 Reservoirs located along the Pecos River including where it intersects with the Capitan Reef Complex Aquifer near Carlsbad, New Mexico.

4.5 Hydraulic Properties

There is a paucity of hydraulic property data for the Capitan Reef Complex Aquifer, especially in Texas. The ability of the aquifer to transmit groundwater to a well varies greatly. Factors impacting the ability of the aquifer to transmit groundwater include: aquifer lithology, karstification—dissolution of the limestone that makes up the aquifer, structural deformation, and fracturing. This section reviews the sources of available data describing Capitan Reef Complex Aquifer hydraulic properties. Several hydraulic properties are used to describe groundwater flow in aquifers. The properties discussed here are hydraulic conductivity, transmissivity, coefficient of storage or storativity, and specific capacity. Each of these terms is briefly described below.

Hydraulic conductivity is a measure of the ease with which groundwater can flow through an aquifer. Higher hydraulic conductivity indicates that an aquifer will allow more groundwater flow under the same hydraulic gradient. In this study, units for hydraulic conductivity are expressed in feet per day.

Transmissivity is a term is closely related to hydraulic conductivity but is a function of the saturated thickness of an aquifer. Transmissivity describes the ability of groundwater to flow through the entire saturated thickness of an aquifer. As the saturated thickness increases, the transmissivity increases for a given hydraulic conductivity. In this study, units for transmissivity are expressed in square feet per day.

Storativity—also referred to as the coefficient of storage—is the volume of water that a confined aquifer releases per square foot of surface area per foot decline of water level. Storativity is a dimensionless parameter.

Specific capacity is a measure of well productivity represented by the ratio between the well pumping rate and the corresponding drawdown—decline in water level. In this study, specific capacity is expressed in gallons per minute per foot of drawdown in a well.

4.5.1 Data Sources

Development of hydraulic properties for the Capitan Reef Complex Aquifer in the study area used multiple sources: Brackbill and Gaines (1964); Richey and others (1985); Myers (1969); Hiss, 1973; 1975; Christian and Wuerch, 2012; Huff, 1997; Garber, and others, 1989; and specific capacity data from drillers' logs on the Texas Water Development Board website (TWDB, 2010b).

Little is known regarding the hydraulic properties of the Capitan Reef Complex Formation in Texas and most of it is semi-quantitative information such as reports of well productivity. Brackbill and Gaines (1964) reported a permeability value of 6 darcies—equivalent to a hydraulic conductivity of 17 feet per day—in Winkler County. Reported well yields in the Capitan Reef Complex Aquifer vary from about 3 gallons per minute up to 6,200 gallons per minute, with a median yield of about 390 gallons per minute (TWDB, 2012b). This suggests a wide range of hydraulic conductivity in the aquifer.

The hydraulic property data for the Capitan Reef Complex in New Mexico and Texas are shown in Figure 4.5.1 and Table 4.5.1. There are no data for this aquifer in Pecos County. Using all sources available, twenty-seven estimates of specific capacity, two estimates of transmissivity, eleven estimates of hydraulic conductivity, and no estimates of storativity were found for the Capitan Reef Complex Aquifer.

4.5.2 Calculation of Hydraulic Conductivity from Specific Capacity

Specific capacity values are calculated from the pumping rate and corresponding drawdown, which are commonly reported in well records. However, hydraulic conductivity or transmissivity are more useful parameters than specific capacity for regional groundwater flow modeling. The following methodology was used to estimate transmissivity from specific capacity data.

Point estimates of aquifer transmissivity can be made based on measurements of specific capacity. In the absence of pump test data, transmissivity can still be estimated using the Cooper-Jacob solution for drawdown in a pumping well (Cooper and Jacob, 1946):

$$s = \frac{Q}{4\pi T} ln\left(\frac{2.25Tt}{r^2 S}\right) \tag{4.5.1}$$

where:

s = drawdown in the well [L],

Q = pumping rate [L3/T],

T = transmissivity [L2/T],

t = time [T],

r = radius of the well [L], and

S = storativity [--].

Equation (5.6.1) can be rearranged to solve for specific capacity as:

$$\frac{Q}{s} = \frac{4\pi T}{ln\left(\frac{2.25Tt}{r^2 S}\right)} \tag{4.5.2}$$

For a given specific capacity, transmissivity can be solved for iteratively. Table 4.5.2 provides specific capacity and calculated transmissivity and hydraulic conductivity data for Capitan Reef Complex Aquifer wells. Transmissivity was calculated using the iterative method outlined by Equation 4.5.2 and assuming a storativity value of 0.0005. Hydraulic conductivity was calculated by dividing the transmissivity by the well screen length or in the absence of screen information by the thickness of the Capitan Reef Complex Aquifer indicated in Figure 4.1.4.

The estimated hydraulic conductivity values for the Capitan Reef Complex Aquifer range from 0.009 to 517 feet per day, with a median of 3 feet per day (Figures 4.5.2 and 4.5.3). A model by INTERA and Cook-Joyce (2012) used a uniform horizontal hydraulic conductivity of 20 feet per day and a vertical hydraulic conductivity of 2 feet per day. Highest hydraulic conductivity in the Capitan Reef Complex Aquifer is associated with karstification of the limestone (Motts, 1968).

Hiss (1975) found that the hydraulic conductivity of the stratigraphic units in the fore-reef Delaware Basin—the Castile Formation and Delaware Mountain Group—are much less than the Capitan Reef Complex Aquifer. The Castile Formation and most units within the Delaware Mountain Group transmit only limited amounts of water (Motts, 1968). Consequently, it is expected that inter-aquifer flow between the Capitan Reef Complex Aquifer and the fore-reef Delaware Basin is limited. The differences in water quality in the Delaware Basin and the

Capitan Reef Complex Aquifer adds more evidence that hydrologic interaction is limited (Hiss, 1980). Hydraulic property data for the Delaware Mountain Group indicate hydraulic conductivity in the range of 0.01 to 0.04 feet per day with a average of 0.02 feet per day—much less than the Capitan Reef Complex Aquifer (Hiss, 1975; Huff, 1997).

West of where the Pecos River intersects with Capitan Reef Complex Aquifer in New Mexico, the back-reef or shelf stratigraphic units of the Artesia Group locally have hydraulic conductivities similar to the Capitan Reef Complex Aquifer (Hiss, 1975; 1980). However, east of the Pecos River, the Artesia Group is readily distinguishable from the Capitan Reef Complex Aquifer in terms of hydraulic properties and water quality (Hiss, 1975). The hydraulic conductivity of the Artesia Group correlates to the mineralogy and texture. The carbonate facies generally have low hydraulic conductivity, except near the boundary with the Capitan Reef Complex. The evaporite facies generally have moderate hydraulic conductivity. The overall hydraulic conductivity of the Artesia Group is several orders of magnitude lower east of the Pecos River than west and is generally one to two orders of magnitude lower than the Capitan Reef Complex Aquifer (Motts, 1968; Hiss, 1980). Consequently, one can deduce significant interaction between the Artesia Group and the Capitan Reef Complex Aquifer west of the Pecos River and limited interaction to the east. Hydraulic property data for the Artesia Group indicate hydraulic conductivity in the range of up to 0.9 feet per day with a median of 0.006 feet per day—much less than the Capitan Reef Complex (Figure 4.5.4; Hiss, 1975; Huff, 1997).

Hydraulic conductivity data from the aquifers overlying the Capitan Reef Complex Aquifer—the Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers—were obtained from their respective groundwater availability model or alternative model reports (Ewing and others, 2012; Ewing and others, 2008; Hutchison and others, 2011). In the Rustler Aquifer, hydraulic conductivity lies in the range of 0.001 to 1,000 feet per day with an average of about 1 foot per day (Figure 4.5.5). Some of the highest hydraulic conductivities in the Rustler Aquifer occur where the underlying Salado Formation has been removed by dissolution—which occurs where the Rustler Aquifer overlies the Capitan Reef Complex Aquifer. Dockum Aquifer hydraulic conductivity adjacent to the Capitan Reef Complex Aquifer lies in the range 0.3 to 300 feet per day which is typical for the rest of the Dockum Aquifer (Figures 4.5.6 and 4.5.7). At the regional scale, hydraulic conductivity ranges in the Edwards-Trinity (Plateau) and Pecos Valley aquifers are 30 to 80 feet per day and 5 to 29 feet per day, respectively (Figure 4.5.8).

4.5.3 Storativity

The specific storage of a confined aquifer is defined as the volume of water a unit volume of aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). The storativity is equal to the product of specific storage and aquifer thickness and is dimensionless. For unconfined conditions, the storativity is referred to as the specific yield and is defined as the volume of water an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table (Freeze and Cherry, 1979). Aquifer storage properties are directly related to aquifer porosity in the unconfined portions of an aquifer and aquifer porosity and matrix compressibility in the confined portions of the aquifer.

A literature review was conducted for storativity of the Capitan Reef Complex Aquifer and no estimates were found. INTERA and Cook-Joyce (2012) used storativity of 0.0005 to 0.0015 in their regional groundwater flow model. A wide range of storage values—storativity and specific yield—would be expected in the Capitan Reef Complex Aquifer because it is composed of a complex mixture of different carbonate rock types and additionally displays varying degrees of karstification (Garber and others, 1989). A study of a core extending from the Salado Formation to the top of the Cherry Canyon Formation in the Delaware Group—including entire thickness of the Capitan Formation—in Eddy County, New Mexico, indicates porosity in the Capitan Reef Complex Aquifer of up to 15 percent (Garber and others, 1989).

Table 4.5.1. Hydraulic property data from wells shown in Figure 4.5.1, located within the Capitan Reef Complex Aquifer. T= transmissivity, K = hydraulic conductivity, Q = well discharge, SC = specific capacity.

Map	Well No.	Location	Latitude	Longitude	Source	County	Date	T (ft^2/d)	K (ft/d)	Q (gpm)	SC (gpm/ft)
1	4717317		31.7436	-104.9164	Myers, 1969	Culberson	10/28/1965	16,000	148	2,000	58
2	21.27.05.414	T21S R27E Sec05 414	32.5057	-104.2044	Hiss, 1973	Eddy	8/12/1969		2.4	85	
3	21.28.30.14123	T21S R28E Sec30 14123	32.4558	-104.1247	Hiss, 1973	Eddy	8/9/1961		16	100	
4	4632309		31.6056	-103.0367	White, 1971	Ward	6/28/1957			780	10
5	4632307		31.5989	-103.0336	White, 1971	Ward	6/28/1957			640	7.3
6	4632305		31.6042	-103.0208	White, 1971	Ward	6/28/1957			704	7.3
7	4632306		31.5894	-103.0389	White, 1971	Ward	2/20/1957			288	2.5
8	4632308		31.5917	-103.0306	White, 1971	Ward	2/20/1957			655	8.9
9	4632610		31.5592	-103.0333	White, 1971	Ward	2/20/1957			375	3.4
10	4632611		31.5778	-103.0261	White, 1971	Ward	6/28/1957			435	3.8
11	4632901		31.5333	-103.0006	White, 1971	Ward	7/11/1962			1,310	13
12	21.34.24	T21S R34E Sec 24	32.4652	-104.4238	Hiss, 1975	Lea	1/14/1965		3.0	240	
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	7/8/1962		1.7	270	
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	10/15/1966		3.5		
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	12/14/1966		1.9	328	
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	12/15/1966		1.4		
14	24.36.4	T24S R36E Sec 04	32.2467	-103.2697	Hiss, 1975	Lea	2/28/1968		24	550	
14	24.36.4	T24S R36E Sec 04	32.2467	-103.2697	Hiss, 1975	Lea	2/28/1968		25	550	
15	24.36.16	T24S R36E Sec 16	32.2175	-103.2697	Hiss, 1975	Lea	10/4/1967		4.4	504	
16	4717321		31.7264	-104.8839	Christian/Wuerch, 2012	Culberson	11/21/1971	179,591		1,600	195
17	5238301		30.4753	-103.2633	TWDB, 2012b	Brewster					0.04
18	4702801		31.9147	-104.8017	TWDB, 2012b	Culberson					0.01
19	4703206		31.9597	-104.6819	TWDB, 2012b	Culberson					0.19
20	4709903		31.7650	-104.9164	TWDB, 2012b	Culberson					16.8
21	4710401		31.8006	-104.8478	TWDB, 2012b	Culberson					0.85
22	4718402		31.7081	-104.8581	TWDB, 2012b	Culberson					3
23	4734603		31.4461	-104.7725	TWDB, 2012b	Culberson					22
24	4734902		31.4139	-104.7650	TWDB, 2012b	Culberson					52
25	4743503		31.3278	-104.6714	TWDB, 2012b	Culberson					7
26	4752301		31.2150	-104.5292	TWDB, 2012b	Culberson					5
27	4752601		31.2083	-104.5256	TWDB, 2012b	Culberson					44
28	4752602		31.2033	-104.5189	TWDB, 2012b	Culberson					12
29	4709201		31.8550	-104.9425	TWDB, 2012b	Hudspeth					10
30	4709207		31.8453	-104.9550	TWDB, 2012b	Hudspeth					428
31	4709208		31.8744	-104.9519	TWDB, 2012b	Hudspeth					1.3
32	4717204		31.7336	-104.9344	TWDB, 2012b	Hudspeth					6.5
33	4717208		31.7361	-104.9367	TWDB, 2012b	Hudspeth					12
34	142		32.4260	-104.2773	NMOSE, 2012	Eddy	8/19/1954				147
35	143		32.4027	-104.2497	NMOSE, 2012	Eddy	8/20/1954				381
36	151		32.4252	-104.2504	NMOSE, 2012	Eddy	10/29/1939				275
37	153		32.2924	-104.3460	NMOSE, 2012	Eddy	7/29/1955				0.87
38	154		32.3899	-104.2732	NMOSE, 2012	Eddy	4/6/1955				419
39	155		32.3624	-104.2971	NMOSE, 2012	Eddy	6/2/1955				14.10
40	171		32.3972	-104.2626	NMOSE, 2012	Eddy	2/27/1942				6.40
41	172		32.3972	-104.2626	NMOSE, 2012	Eddy	8/18/1954				32.40
42	229		32.4082	-104.2669	NMOSE, 2012	Eddy	8/20/1954				138
43	230		32.3928	-104.2884	NMOSE, 2012	Eddy	6/2/1955				90
44	250		32.1803	-104.3782	NMOSE, 2012	Eddy	12/8/1954				18.30
45	314		32.4540	-104.1293	NMOSE, 2012	Eddy	1/1/1961	6,700			
46		El Capitan SWS			Brackbill & Gaines, 1964	Winkler			17		

Table 4.5.2 Specific capacity data and calculated hydraulic conductivity based on Equation 4.5.2 for wells in the Capitan Reef Complex Aquifer. The map number refers to location numbers in Figure 4.5.1.

Map	Well Number	County	Specific Capacity (gpm/ft)	Drawdown (ft)	Pump Rate (gpm)	Time (h)	Well Diameter (in)	Screen Length (ft)	Transmissivity (ft^2/d)	Hydraulic Conductivity (ft/d)
17	5238301	Brewster	0.04	82	5	5	8	839	9.5	0.011
18	4702801	Culberson	0.01	364	4	161	6	220	2.0	0.009
19	4703206	Culberson	0.19	25	5	2.5	4	60	35.1	0.58
20	4709903	Culberson	16.8	39	656	8	16	375	3,961	10.56
21	4710401	Culberson	0.85	20	17	24	8	799	193.0	0.24
1	4717317	Culberson	58	34	2,000	24	16	70	16,162	231
16	4717321	Culberson	219	7.3	1,600	12	16	564	62,485	110.8
22	4718402	Culberson	3	104	279	12	12	1,513	593	0.39
23	4734603	Culberson	22	103	2,250	24	14	192	5,739	29.9
24	4734902	Culberson	52	49	2,550	23	14	61	14,387	236
25	4743503	Culberson	7	83	550	36	14	321	1,654	5.15
26	4752301	Culberson	5	82	379	2.5	18	550	878	1.60
27	4752601	Culberson	44	9	396	51	18	155	12,256	79.1
28	4752602	Culberson	12	88	1,100	27	18	309	3,087	9.99
29	4709201	Hudspeth	10	3	30	4	6	204	2,480	12.16
30	4709207	Hudspeth	428	3.5	1,500	4	14	234	121,035	517
31	4709208	Hudspeth	1.3	19	25	24	7	135	314	2.33
32	4717204	Hudspeth	6.5	88	570	24	18	830	1,515	1.83
33	4717208	Hudspeth	12	168	2,000	24	18	1,540	2,907	1.89
6	4632305	Ward	7.3	97	778	5	13	178	1,781	10.01
7	4632306	Ward	2.5	113	288	24	13	713	584	0.82
5	4632307	Ward	7.3	88	640	5	10	3,100	1,668	0.54
8	4632308	Ward	8.9	74	655	24	13	564	2,214	3.93
4	4632309	Ward	10	78	780	5	13	455	2,258	4.96
9	4632610	Ward	3.5	110	385	5	13	799	728	0.91
10	4632611	Ward	3.8	115	435	5	13	596	792	1.33
11	4632901	Ward	13	101	1,310	4	9	1,096	3,097	2.83
34	142	Eddy	147	10	1,470	8	12		40,347	23.06
35	143	Eddy	381	7	2,670	8	16		107,029	61.16
36	151	Eddy	275	3	833	8	12		78,271	44.73
37	153	Eddy	0.87	23	20	1	12		125	0.07
38	154	Eddy	419	1	419	8	6		131,482	75.13
39	155	Eddy	14.10	17	240	1	8		2,947	1.68
40	171	Eddy	6.40	25	160	5	12		1,368	0.78
41	172	Eddy	32.40	18	550	5	13		7,291	4.17
42	229	Eddy	138	7	1,238	8	14		48,188	27.54
43	230	Eddy	90	23	350	1	12		3,085	1.76
44	250	Eddy	18.30	6	110	54	12		4,981	2.85

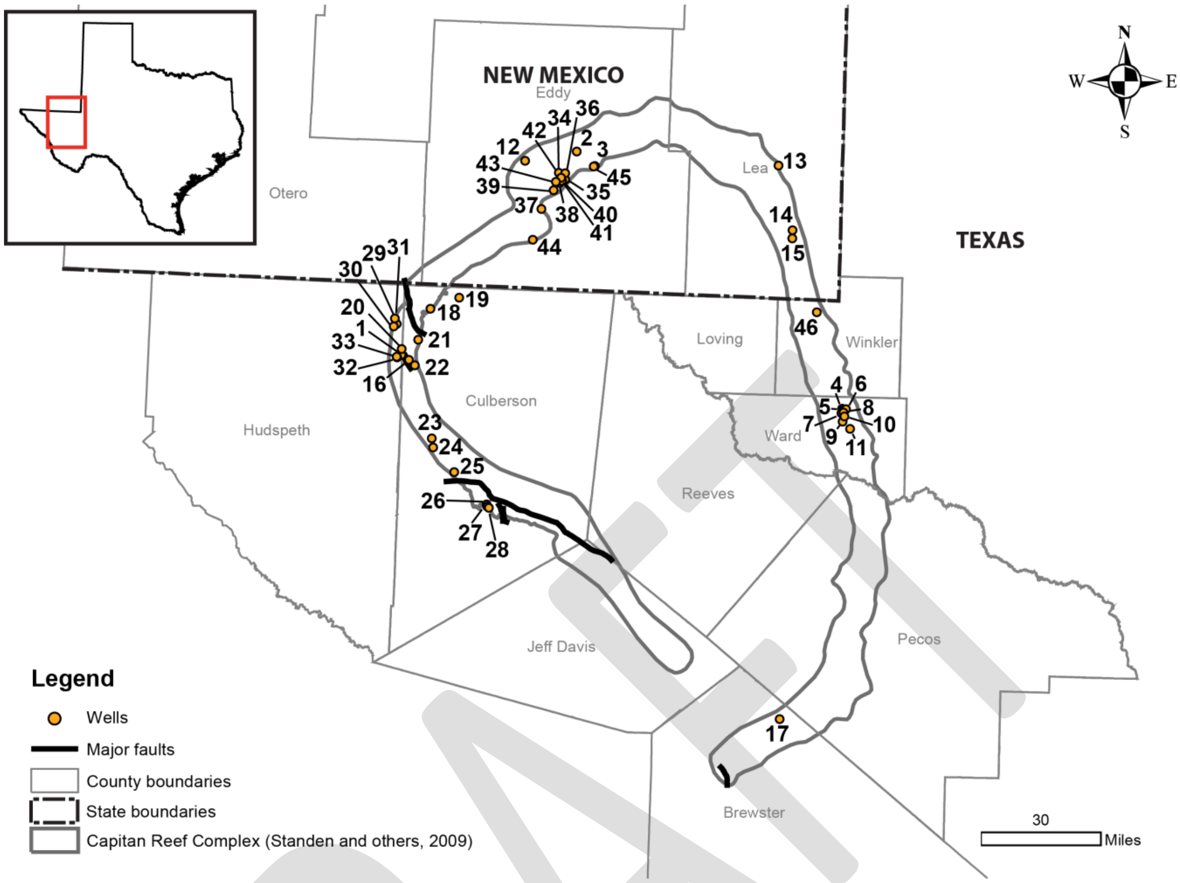


Figure 4.5.1 Hydraulic property data locations for the Capitan Reef Complex Formation in Texas and New Mexico. The numbers refer to wells in Table 4.5.1 and includes references for the source of data.

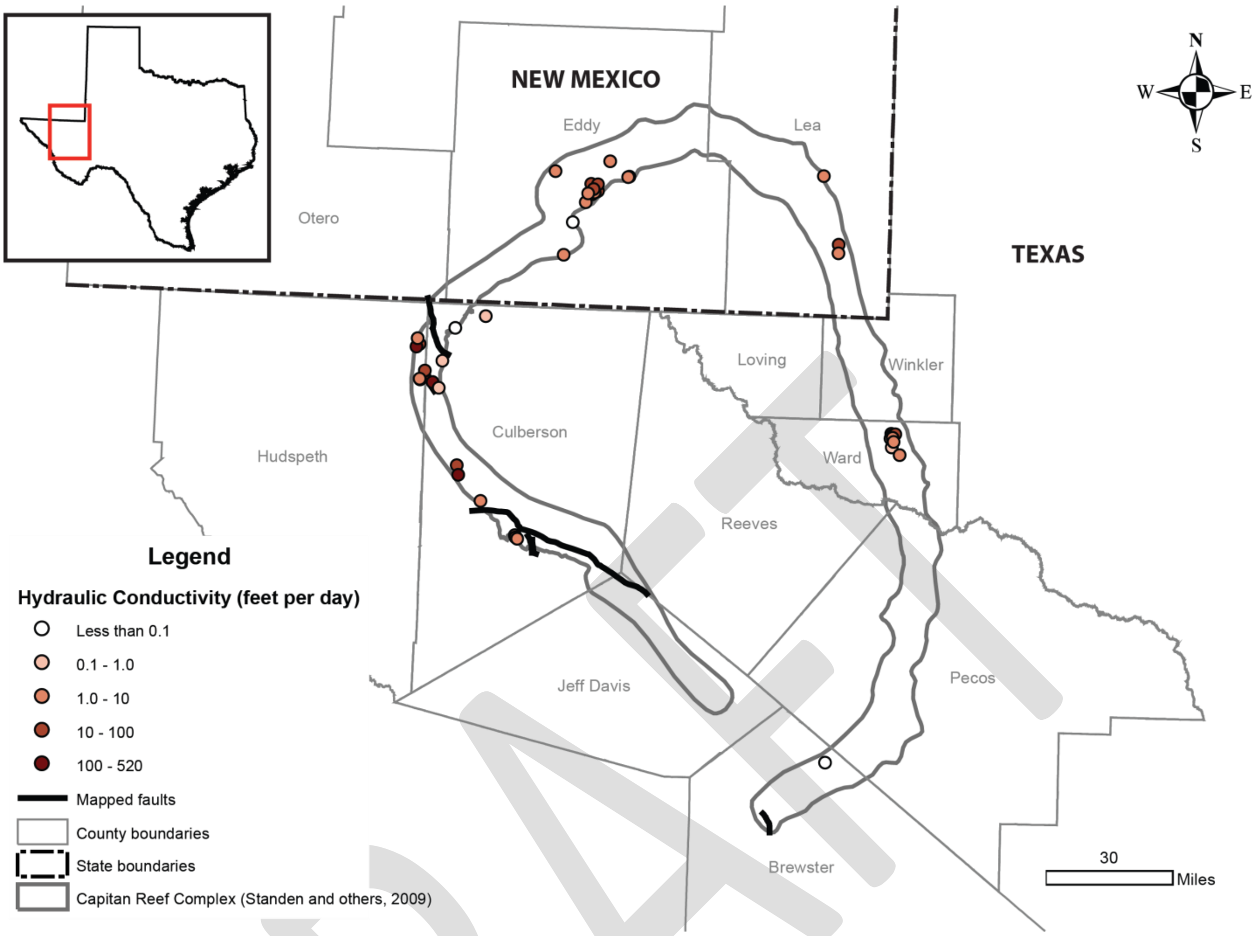


Figure 4.5.2 Hydraulic conductivity data for the Capitan Reef Complex Aquifer in Texas and New Mexico (see Table 4.5.1 for references of the source of data).

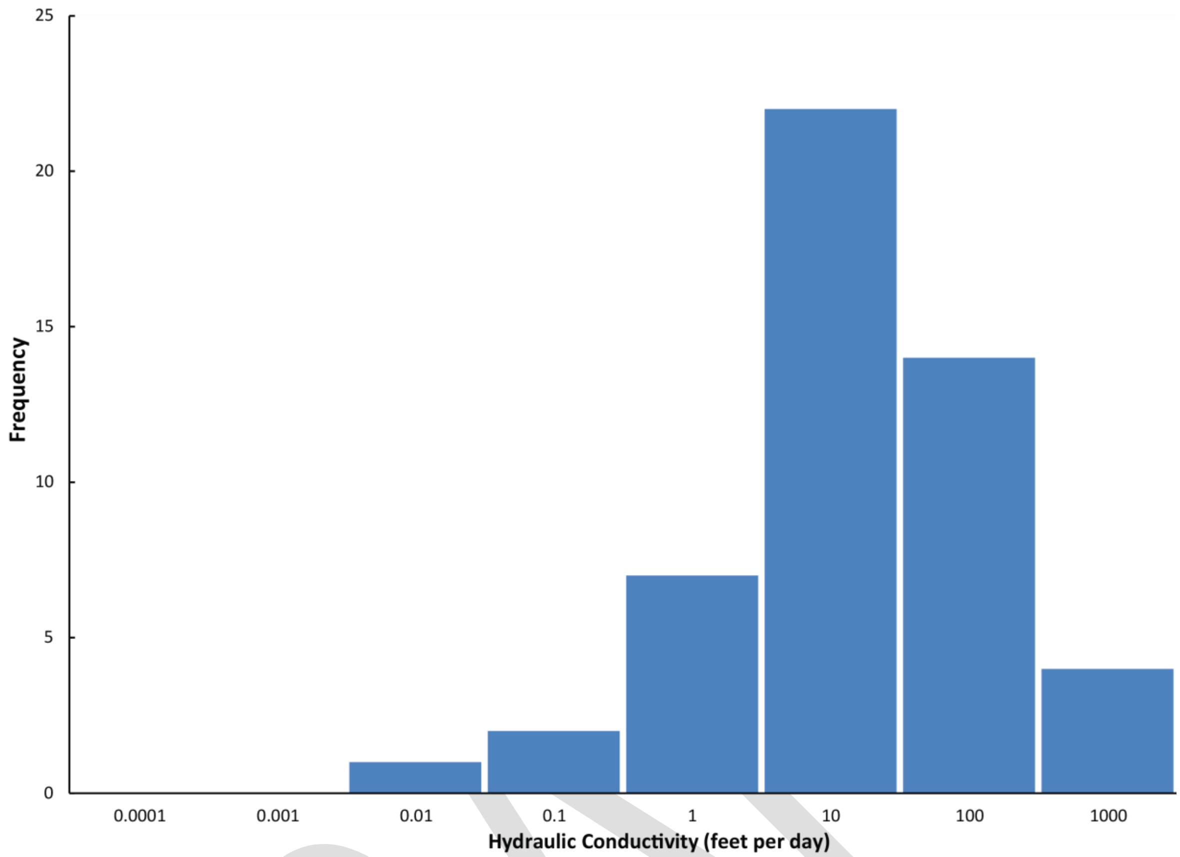


Figure 4.5.3 Histogram of hydraulic conductivity data in feet per day for the Capitan Reef Complex Aquifer based on data from the sources indicated in Table 4.5.1.

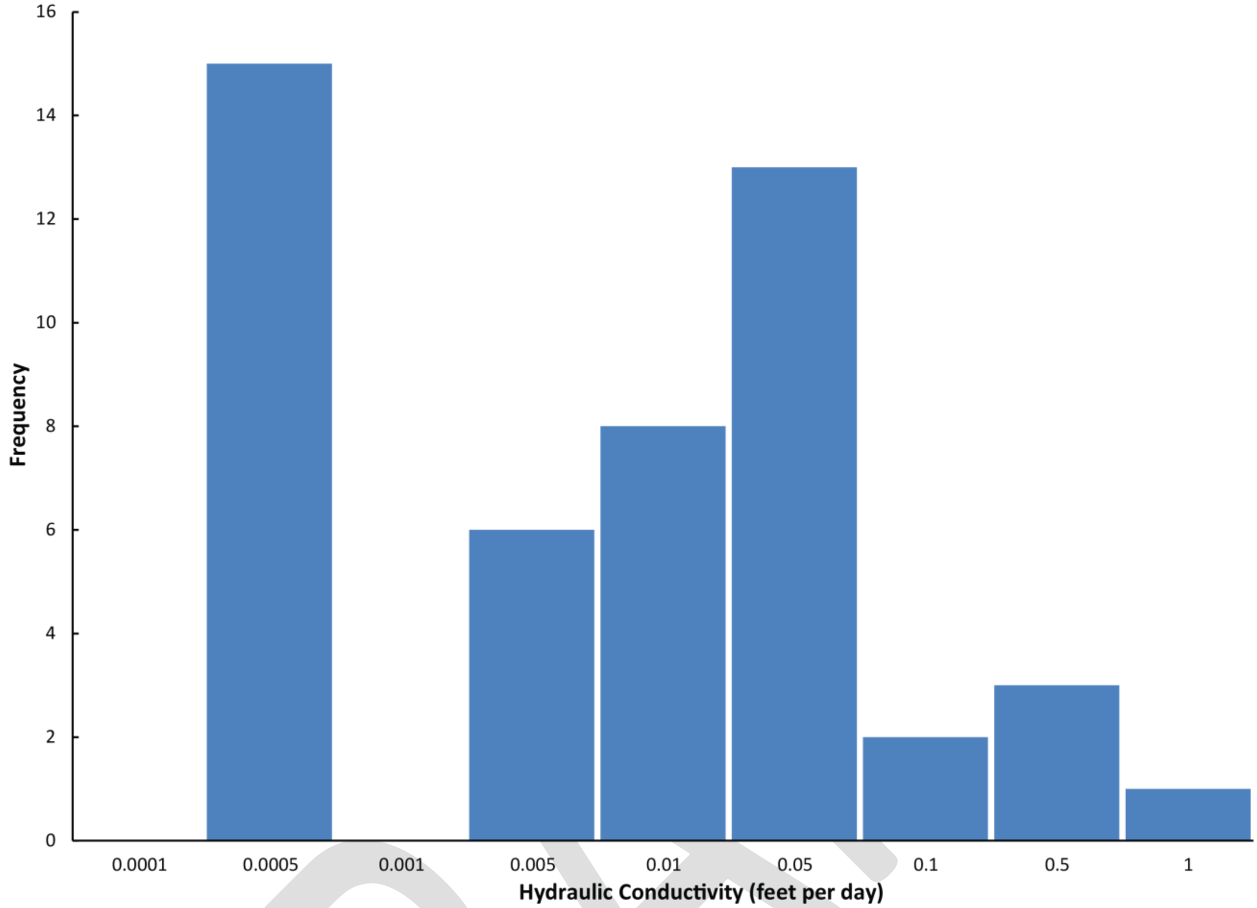


Figure 4.5.4 Histogram of hydraulic conductivity data in feet per day for the Artesia Group based on data from Huff (1997).

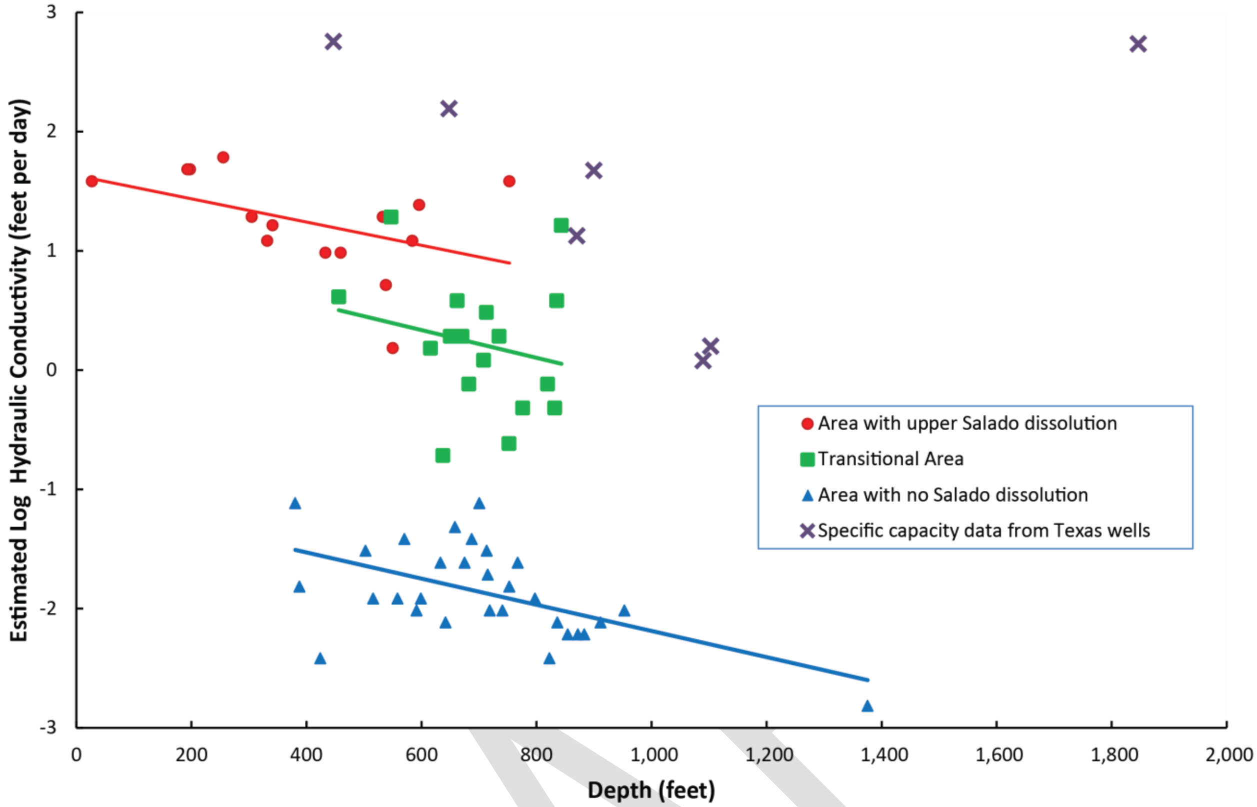


Figure 4.5.5 Hydraulic conductivity data for the Rustler Aquifer in Texas and New Mexico (From Ewing and others, 2012).

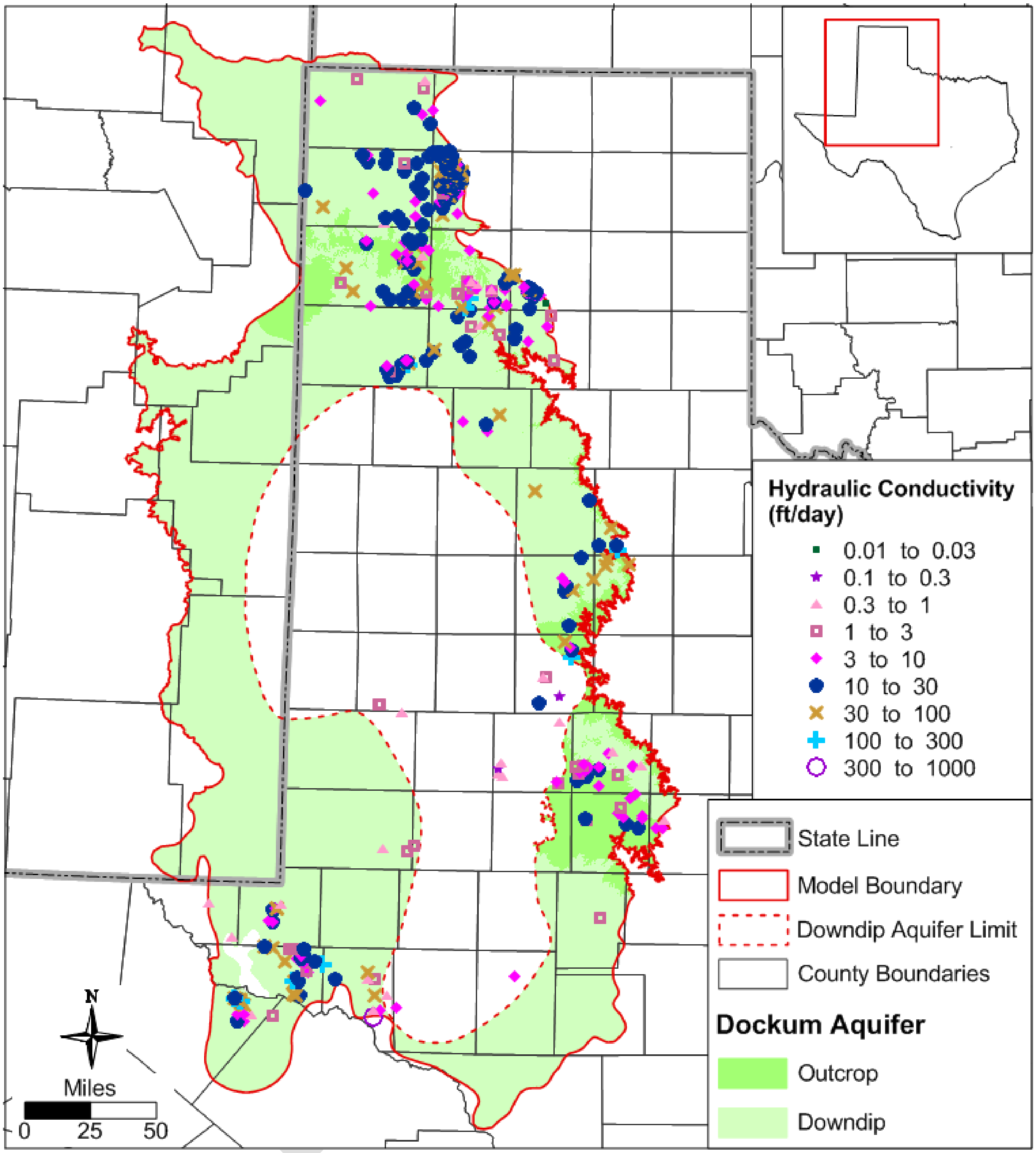


Figure 4.5.6 Hydraulic conductivity data for the Dockum Aquifer in Texas and New Mexico (From Ewing and others, 2008).

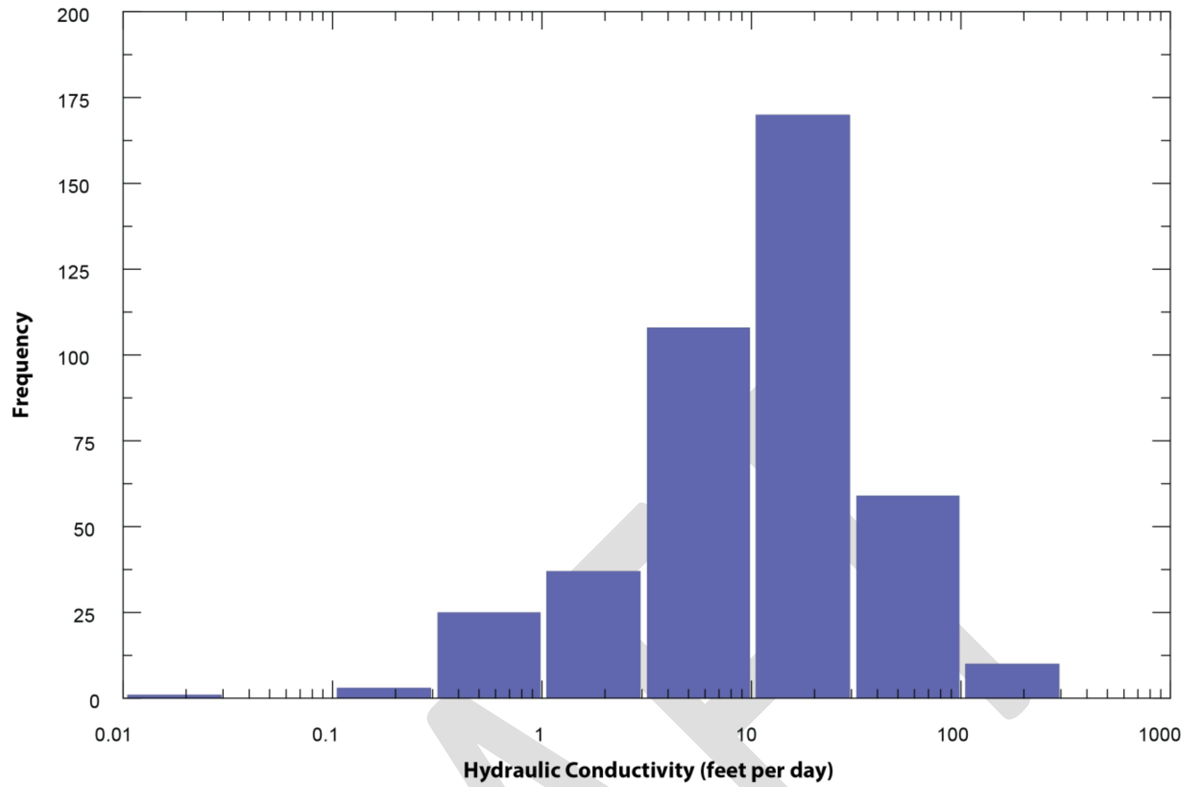


Figure 4.5.7 Histogram of hydraulic conductivity data in feet per day for the Dockum Aquifer (modified from Ewing and others, 2008).

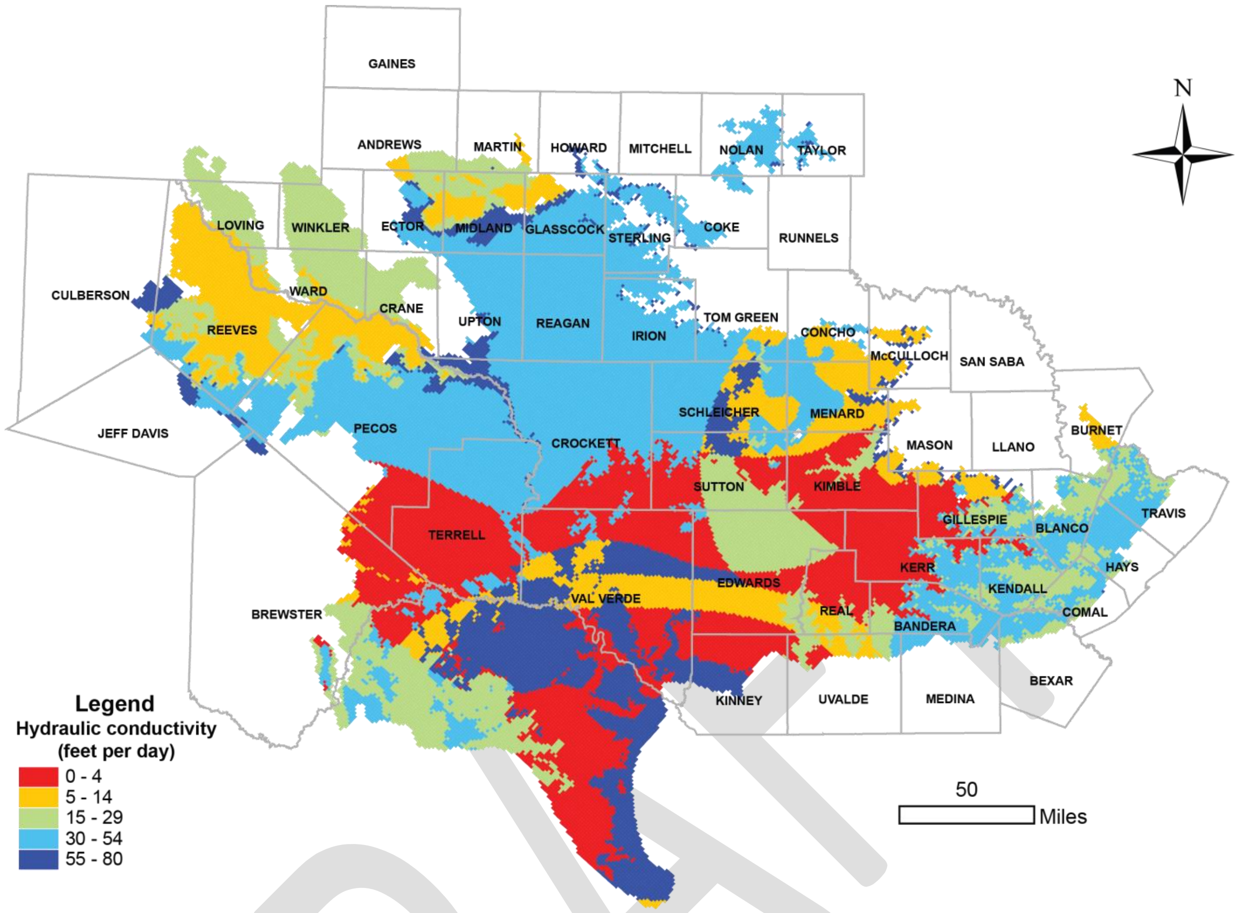


Figure 4.5.8 Hydraulic conductivity data for the Edwards-Trinity and Pecos Valley aquifers in Texas and New Mexico (From Hutchison and others, 2011).

4.6 Discharge

The term, discharge, refers to processes by which water leaves an aquifer. These processes include both natural and anthropogenic processes. Groundwater discharges from aquifers naturally through flow to streams or springs, evapotranspiration, and cross-formational flow. Pumping wells is an anthropogenic form of discharge from aquifers.

4.6.1 Natural Aquifer Discharge

In a typical topographically-driven flow system, percolation of precipitation results in recharge at the water table, which flows from topographic highs and discharges at topographic lows through streams and springs, and groundwater evapotranspiration. Water that moves down-dip eventually discharges upward through cross-formational flow. In the Capitan Reef Complex Aquifer, likely forms of discharge are flow into the Pecos River in New Mexico and cross-formational form where the aquifer occurs in the subsurface.

Discharge through baseflow from the Capitan Reef Complex Aquifer to the Pecos River in New Mexico is discussed in Sections 4.4.1 through 4.4.3. This discharge limits southward groundwater flow into the eastern arm of the Capitan Reef Complex Aquifer (Figure4.2.2).

Discharge via cross-formational flow is mentioned in Section 4.2. Cross-formational flow is likely the largest form of discharge from the Capitan Reef Complex Aquifer considering the limited access to perennial streams and wetlands—sites for baseflow and evapotranspiration discharge from the aquifer—where the aquifer crops out. Evidence supporting cross-formational flow as the main form of discharge are: (1) few perennial streams crossing aquifer outcrops; (2) northward and southward flow paths converging in Winkler and Ward counties; (3) the occurrence of artesian wells and springs like the Diamond Y Spring that discharge water derived from underlying aquifers (Veni, 1991; Boghici and Van Broekhoven, 2001); and (4) Capitan Reef Complex Aquifer water levels that are consistently higher than water levels in overlying aquifers (Figures 4.2.1, 4.2.3, 4.2.6, 4.2.12). The collapse structure that resulted from the dissolution of the overlying Salado Formation and resultant subsidence of the overlying stratigraphic units acts as a potential pathway for upward groundwater flow through—and mixing with—Rustler, Dockum, and Pecos Valley aquifer groundwater. This collapse structure is responsible for the formation of the Monument Draw Trough in the Pecos Valley Aquifer (Jones, 2001; 2004) and also approximately coincides with the eastern arm of the Capitan Reef Complex Aquifer (Figure 4.6.1).

4.6.2 Aquifer Discharge through Pumping

Estimates of groundwater pumping from the Capitan Reef Complex Aquifer throughout Texas for the years 1980 through 2008 were obtained from the Texas Water Development Board historical water use estimates. The six water-use categories defined in the Texas Water Development Board database are municipal, manufacturing, steam electric generation, irrigation, mining, and livestock. Rural domestic pumping is likely to be very small relative to the other pumping categories because of low population, poor water quality, and the fact that the Capitan Reef Complex Aquifer is overlain by other aquifers that have better water quality and are consequently more attractive sources of groundwater. The water use estimates for the Capitan Reef Complex Aquifer indicate pumping from Brewster, Culberson, Hudspeth, Pecos, and Ward counties, and no pumping for Winkler County.

In the groundwater availability model for the Capitan Reef Complex Aquifer, pumping data for overlying aquifers—Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers—will be derived from the respective groundwater availability models (Ewing and others, 2008; 2012; Hutchison and others, 2011). It will be assumed that due to low groundwater yield and poor water quality issues that pumping from the non-aquifer stratigraphic units in the study area—the Artesia and Delaware Mountain groups, and the Castile and Salado formations—is insignificant.

The Texas Water Development Board water use survey indicates that mining pumpage is primarily attributable to oil and gas operations. Figure 4.6.2A shows the spatial distribution of oil and gas wells drilled since 1928 that penetrate the Capitan Reef Complex Aquifer. These wells—mostly located on the eastern arm of the Capitan Reef Complex—were used to extract or explore for oil and gas in underlying stratigraphic units including the Wolfcamp, Spraberry, Canyon, Clear Fork, San Andres, and Grayburg formations (Nicot and others, 2012). In some cases, the Capitan Reef Complex Aquifer is used as a source of water for use in oil and gas well fields (Brackbill and Gaines, 1964). It is likely that petroleum-related pumping from the Capitan Reef Complex Aquifer will vary with oil and gas activity (Figure 4.6.2B). Figure 4.6.2 shows wide fluctuations in the number of oil and gas wells drilled per year. Over the period 2000 to 2010, the number of oil and gas wells penetrating the Capitan Reef Complex Aquifer per year varied from a high of 288 wells in 2006 to a low of 55 wells in 2002. However, there is a general trend towards increased drilling over time. Thus it is expected that petroleum-related pumping is gradually rising over time with the number of oil and gas wells in the area.

Nicot and others (2011; 2012) indicate that there are five categories of petroleum-related pumping—well completion in tight formations, enhanced oil recovery, waterflooding, drilling, and hydraulic fracturing. The term tight-formation completion refers to hydraulic fracturing of low permeability reservoir rock to increase oil and/or gas production. Enhanced oil recovery is a term for techniques that increase the amount of oil that can be extracted from an oil reservoir. Waterflooding is the injection of water into and oil or gas reservoir in order to maintain pressure. The water used for drilling oil and gas wells that is reported in Nicot and others (2011) is an estimate based on informal discussions with practicing field engineers. Hydraulic fracturing refers to water used to fracture source rocks, such as shales, in order to extract gas. Hydraulic fracturing water use is subdivided into use and consumption. Water use refers to the amount of water used regardless of the water source, while water consumption excludes recycled and reused water. In the study area, there is no petroleum-related pumping in Brewster, Hudspeth, and Jeff Davis counties (Table 4.6.1). Overall, highest petroleum-related pumping occurs in Pecos County, although the highest rates of water consumption related to hydraulic fracturing occur in Ward County (Figure 4.6.3).

Irrigation pumping from the Capitan Reef Complex Aquifer is likely to be minimal considering issues of aquifer depth, groundwater quality, and the occurrence of alternative sources of irrigation water. Texas Water Development Board pumping data for the Capitan Reef Complex Aquifer indicate irrigation pumping up to 8,600 acre-feet per year—mostly in Culberson, Hudspeth, and Pecos counties (Figure 4.6.4; Table 4.6.2).

Livestock pumping was distributed using land cover data obtained from the National Land Cover Dataset (Vogelman and others, 1998a; 1998b). We assume that livestock pumping is associated with grassland and scrubland land cover (Figure 4.6.5A). These types of land cover account for almost all of the land cover over the Capitan Reef Complex Aquifer, however, livestock pumping is unlikely to occur much beyond the Capitan Reef Complex outcrops. Figure 4.6.5B shows the area most likely to be used for livestock pumping—where the depth to the Capitan Reef Complex Aquifer is less than 600 feet, the average depth of livestock wells pumping from the aquifer. Estimates of livestock pumping from the Capitan Reef Complex Aquifer are low, less than 100 acre-feet per year (Table 4.6.3).

Manufacturing and municipal pumping are spatially distributed based on known well locations (Figure 4.6.6). Texas Water Development Board pumping data indicates very little municipal pumping and almost no manufacturing and steam electric pumping from the Capitan Reef Complex Aquifer (Tables 4.6.4 and 4.6.5). Estimated pumping from the Texas Water Development Board water use survey indicate total municipal pumping from the Capitan Reef Complex Aquifer in the range of 1 to 20 acre-feet per year and no manufacturing pumping since 1982.

Rural domestic pumping—which consists primarily of unreported domestic water use—is assumed to: (1) be related to the population density in non-urban areas (Figure 4.6.7A), and (2) occur only in and adjacent to the Capitan Reef Complex Aquifer outcrops—in an area defined by an aquifer depth less than 900 feet which is the average depth of Capitan Reef Complex Aquifer domestic wells (Figure 4.6.7B). Capitan Reef Complex Aquifer rural domestic pumping is expected to be very small because most parts of the aquifer with this category of pumping have population densities of 0 to 1 persons per square mile (Table 4.6.6). Rural domestic pumping estimates are based partially on per capita water usage rate estimates. Estimates of per capita water vary from 110 gallons per day to as high as 500 gallons per day. The highest estimates—based on county-wide municipal pumping and urban populations—are high because they also incorporate some commercial pumping that use "city water".

Table 4.6.1 County-wide estimates of different categories of petroleum-related pumping in the Texas portion of the study area. The data was taken from Nicot and others (2011; 2012).

County	Tight Formation Completion (acre-feet)	Enhanced Oil Recovery (acre-feet)	Waterfloods (acre-feet)		Drilling (acre-feet)	Hydraulic Fracturing Use (acre-feet)	Hydraulic Fracturing Consumption (acre-feet)
	2008	1995	2008	2010	2008	2011	2011
Brewster	0	0	0	0	0	0	0
Culberson	12	0	115	160	0	166	33
Hudspeth	0	0	0	0	0	0	0
Jeff Davis	0	0	0	0	0	0	0
Pecos	183	162	267	315	206	110	22
Ward	67	9	13	15	84	568	114
Winkler	14	47	87	105	57	62	12

Table 4.6.2 Estimates of Capitan Reef Complex Aquifer irrigation pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	60	2,800	0	0	0
1981	0	50	2,125	0	0	0
1982	0	41	1,449	0	0	0
1983	0	31	774	0	0	0
1984	0	21	98	0	0	0
1985	0	25	80	0	0	0
1986	0	19	37	0	0	0
1987	0	20	40	0	0	0
1988	0	19	46	0	0	0
1989	0	14	81	0	0	0
1990	0	9	42	0	0	0
1991	0	9	43	0	0	0
1992	0	11	33	0	0	0
1993	0	6	97	0	0	0
1994	0	0	2,797	0	0	0
1995	0	0	2,224	0	0	0
1996	0	0	2,084	0	0	0
1997	0	0	2,094	0	0	0
1998	0	0	2,436	0	0	0
1999	0	0	3,701	0	0	0
2000	0	0	3,532	0	0	0
2001	0	0	3,121	0	0	0
2002	0	0	2,769	0	0	0
2003	0	0	2,463	0	0	0
2004	0	3,151	2,828	918	0	0
2005	0	3,594	2,363	888	0	0
2006	0	3,366	1,522	1,337	0	0
2007	0	2,749	1,766	1,179	0	0
2008	0	5,651	1,713	1,229	0	0

Table 4.6.3 Estimates of Capitan Reef Complex Aquifer livestock pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	41	11	0	0	0
1981	0	38	11	0	0	0
1982	0	36	10	0	0	0
1983	0	33	10	0	0	0
1984	0	30	9	0	0	0
1985	0	33	5	0	0	0
1986	0	28	3	0	0	0
1987	0	44	5	0	0	0
1988	0	47	5	0	0	0
1989	0	47	5	0	0	0
1990	0	46	5	0	0	0
1991	0	47	5	0	0	0
1992	0	31	6	0	0	0
1993	0	29	6	0	0	0
1994	0	26	8	0	0	0
1995	0	21	6	0	0	0
1996	0	23	5	0	0	0
1997	0	25	5	0	0	0
1998	0	34	9	0	0	0
1999	0	37	9	0	0	0
2000	0	33	8	0	0	0
2001	0	30	8	0	0	0
2002	0	47	8	0	0	0
2003	0	25	6	0	0	0
2004	21	50	6	14	0	0
2005	27	41	5	15	0	0
2006	25	47	6	17	0	0
2007	27	53	6	13	0	0
2008	30	55	6	15	0	0

Table 4.6.4 Estimates of Capitan Reef Complex Aquifer manufacturing pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	0	1.00	0	0	0
1981	0	0	0.75	0	0	0
1982	0	0	0.50	0	0	0
1983	0	0	0.25	0	0	0
1984	0	0	0	0	0	0
1985	0	0	0	0	0	0
1986	0	0	0	0	0	0
1987	0	0	0	0	0	0
1988	0	0	0	0	0	0
1989	0	0	0	0	0	0
1990	0	0	0	0	0	0
1991	0	0	0	0	0	0
1992	0	0	0	0	0	0
1993	0	0	0	0	0	0
1994	0	0	0	0	0	0
1995	0	0	0	0	0	0
1996	0	0	0	0	0	0
1997	0	0	0	0	0	0
1998	0	0	0	0	0	0
1999	0	0	0	0	0	0
2000	0	0	0	0	0	0
2001	0	0	0	0	0	0
2002	0	0	0	0	0	0
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	0	0	0	0	0	0
2006	0	0	0	0	0	0
2007	0	0	0	0	0	0
2008	0	0	0	0	0	0

Table 4.6.5 Estimates of Capitan Reef Complex Aquifer municipal pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	10	2	0	0	0
1981	0	11	2	0	0	0
1982	0	11	2	0	0	0
1983	0	12	1	0	0	0
1984	0	12	1	0	0	0
1985	0	10	1	0	0	0
1986	0	8	1	0	0	0
1987	0	9	1	0	0	0
1988	0	9	1	0	0	0
1989	0	7	1	0	0	0
1990	0	5	1	0	0	0
1991	0	5	1	0	0	0
1992	0	5	1	0	0	0
1993	0	6	1	0	0	0
1994	0	0	1	0	0	0
1995	0	5	1	0	0	0
1996	0	5	1	0	0	0
1997	0	4	1	0	0	0
1998	0	5	1	0	0	0
1999	0	6	1	0	0	0
2000	0	4	1	0	0	0
2001	0	4	1	0	0	0
2002	0	4	1	0	0	0
2003	0	4	1	0	0	0
2004	3	12	4	0	0	0
2005	3	12	4	0	0	0
2006	3	13	4	0	0	0
2007	3	10	3	0	0	0
2008	3	11	3	0	0	0

Table 4.6.6 County-wide estimates of rural domestic pumping in Capitan Reef Complex Aquifer the study area. The data was obtained from the United States Department of Commerce (2013).

County	Rural Population (2000)	Rural Domestic Pumpage (2000) (acre-feet)
Brewster	2,085	257
Culberson	386	48
Eddy	10,091	1,243
Hudspeth	2,911	359
Jeff Davis	2,031	250
Lea	8,595	1,059
Loving	67	8
Otero	15,204	1,873
Pecos	6,587	811
Reeves	1,454	179
Ward	1,871	230
Winkler	215	26

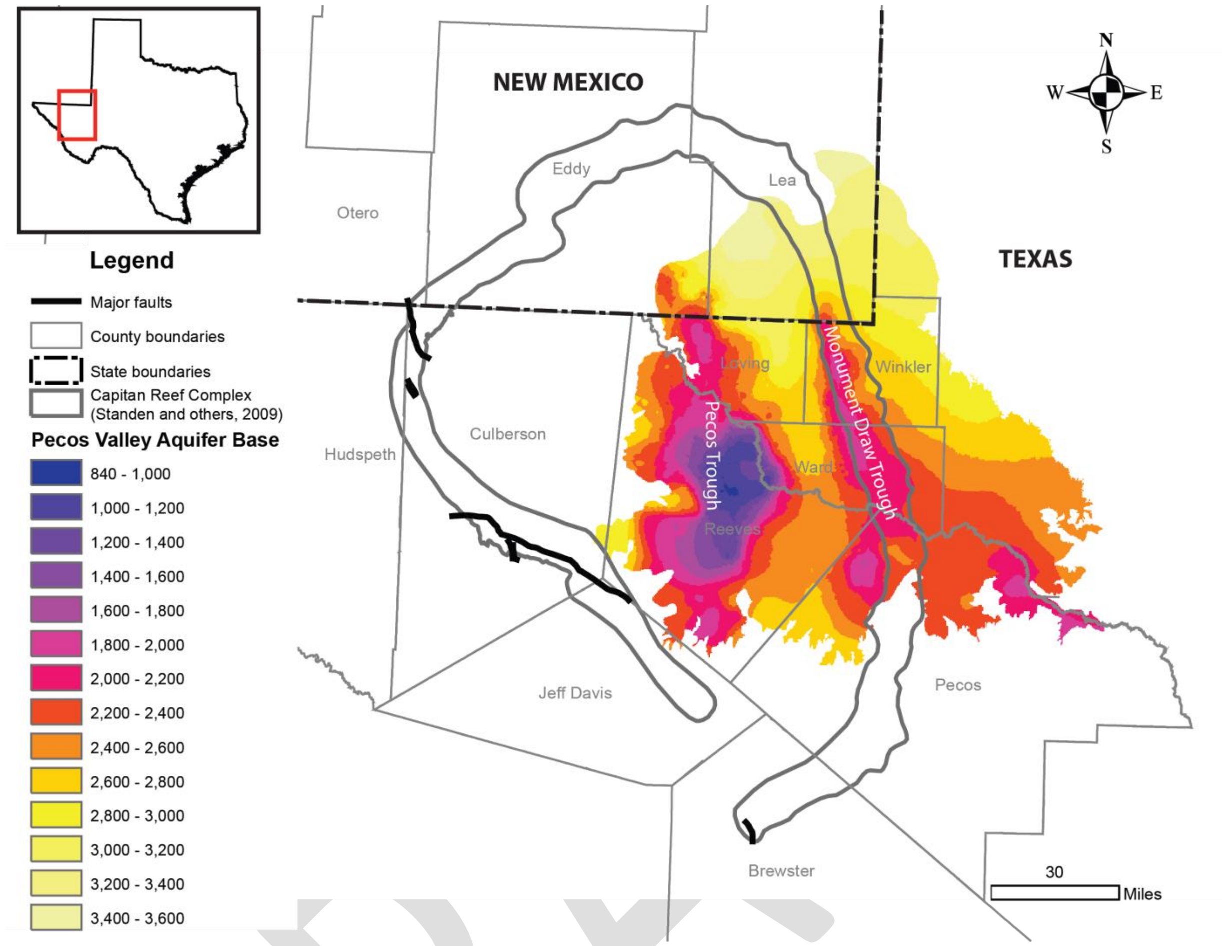
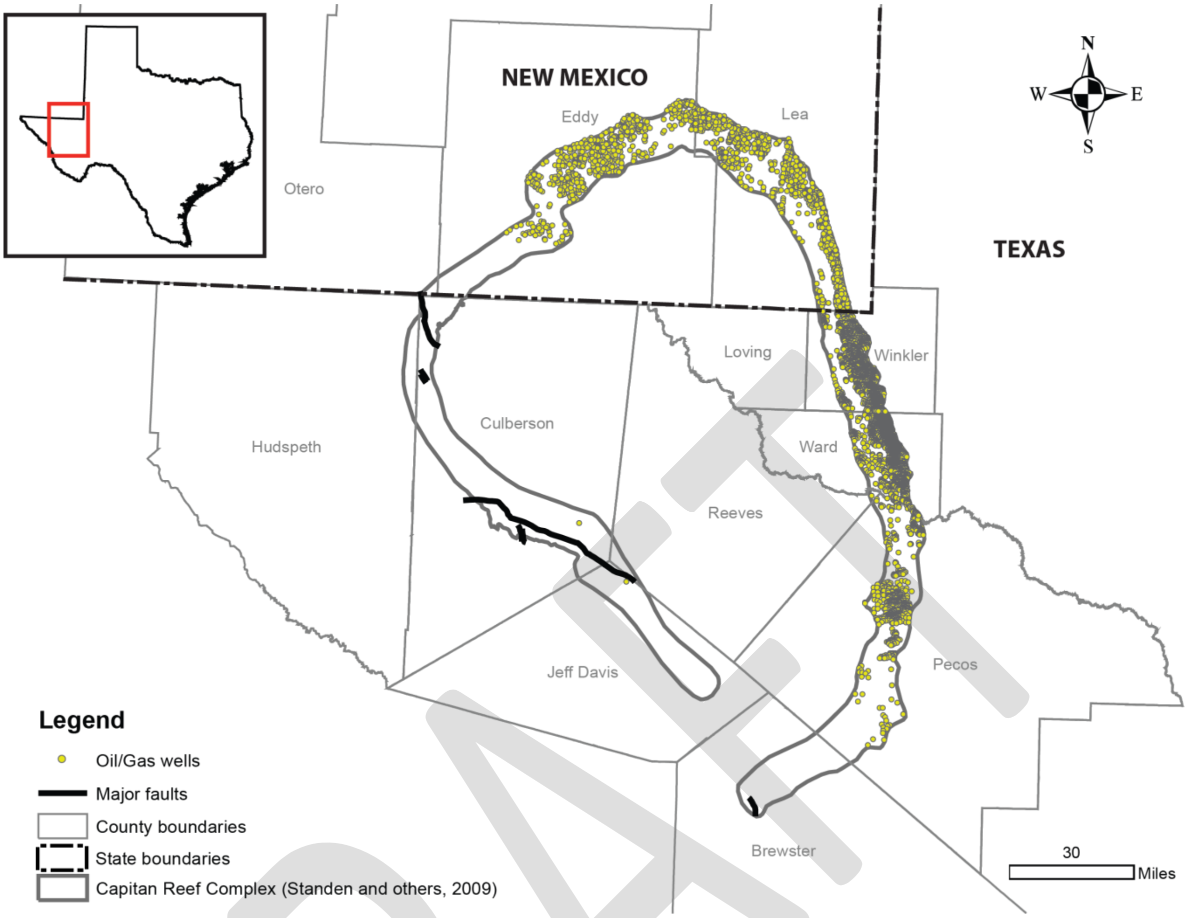
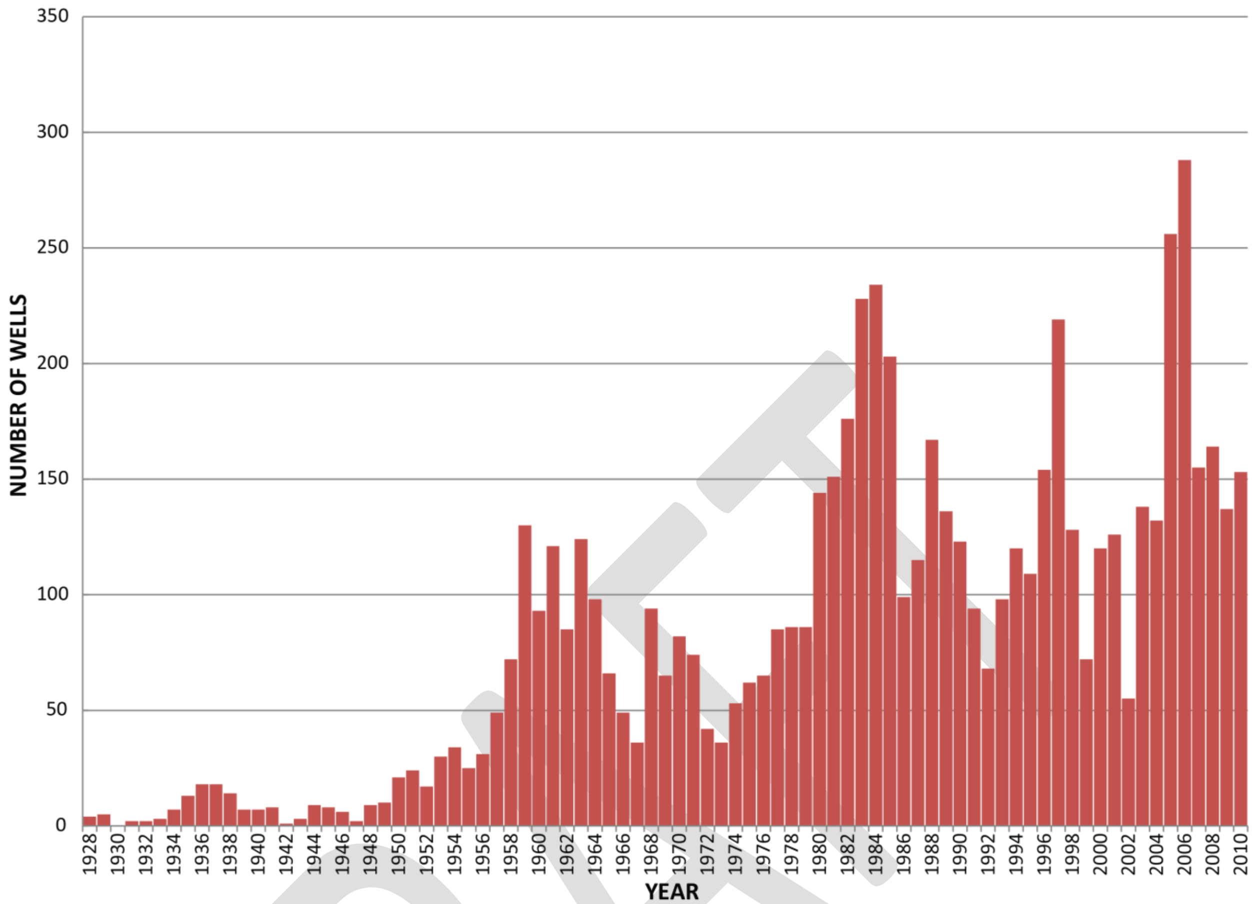


Figure 4.6.1 The eastern arm of the Capitan Reef Complex Aquifer coincides with the Monument Draw Trough of the overlying Pecos Valley. The formation of the Monument Draw Trough is the result of dissolution of the Salado Formation—a stratigraphic unit overlying the Capitan Reef Complex—and consequent collapse of overlying stratigraphic units. This collapse structure potentially forms a pathway for upward discharge of groundwater. (Pecos Valley Aquifer base data from Hutchison and others, 2011).



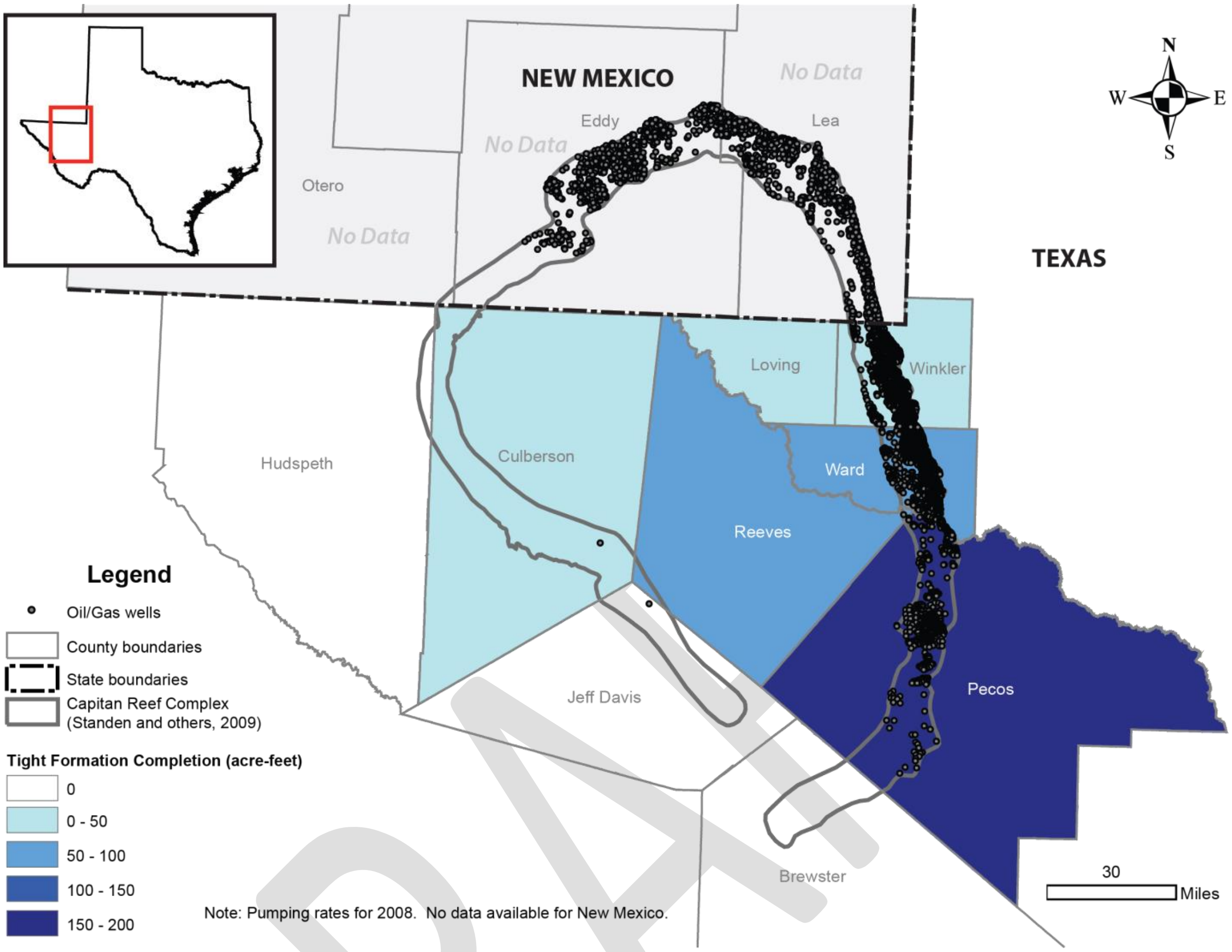
(A)

Figure 4.6.2 Spatial (A) and temporal (B) distribution of oil and gas wells penetrating the Capitan Reef Complex Aquifer (Railroad Commission of Texas, 2012; New Mexico Energy, Minerals and Natural Resources Department, 2012).



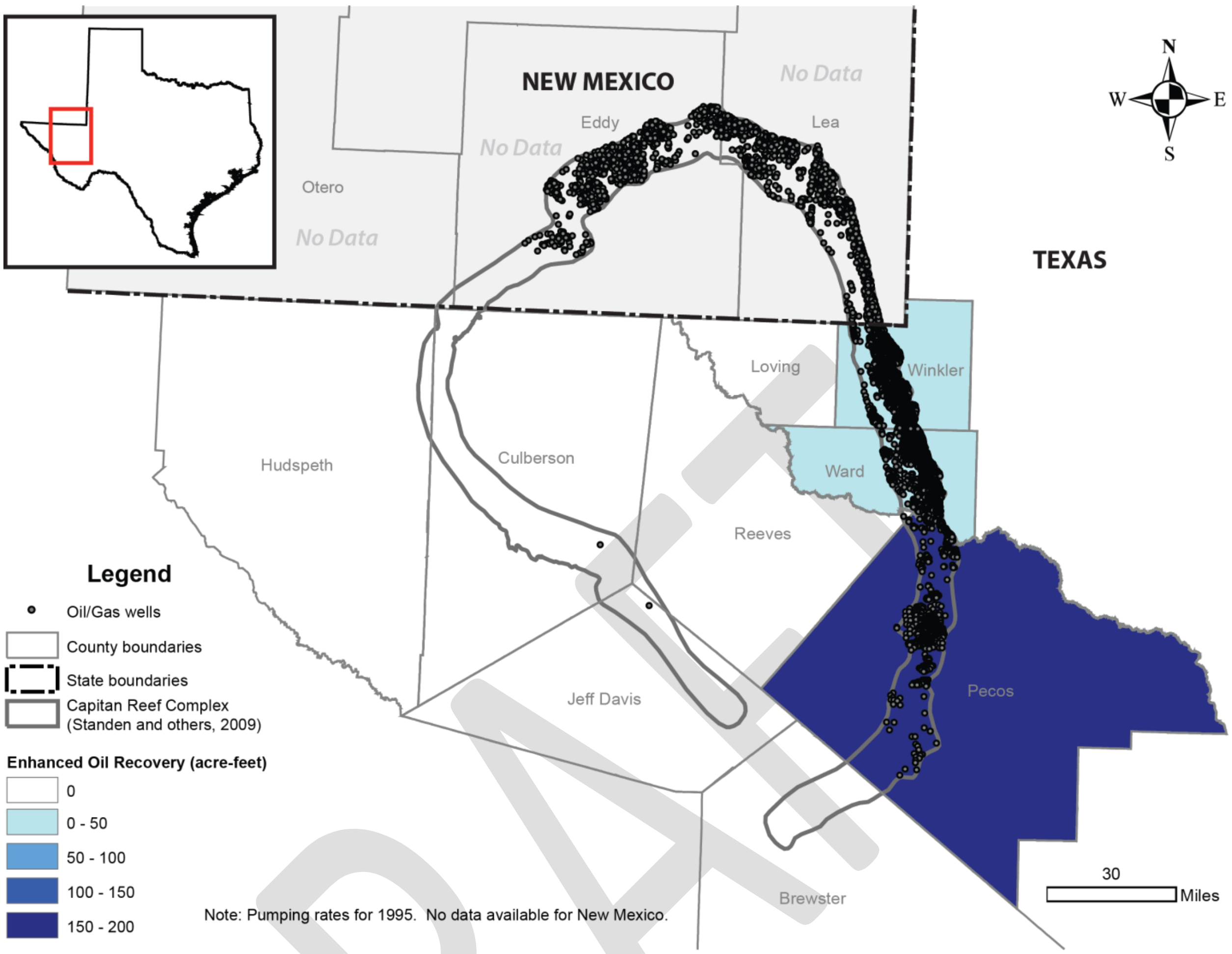
(B)

Figure 4.6.2 (continued)



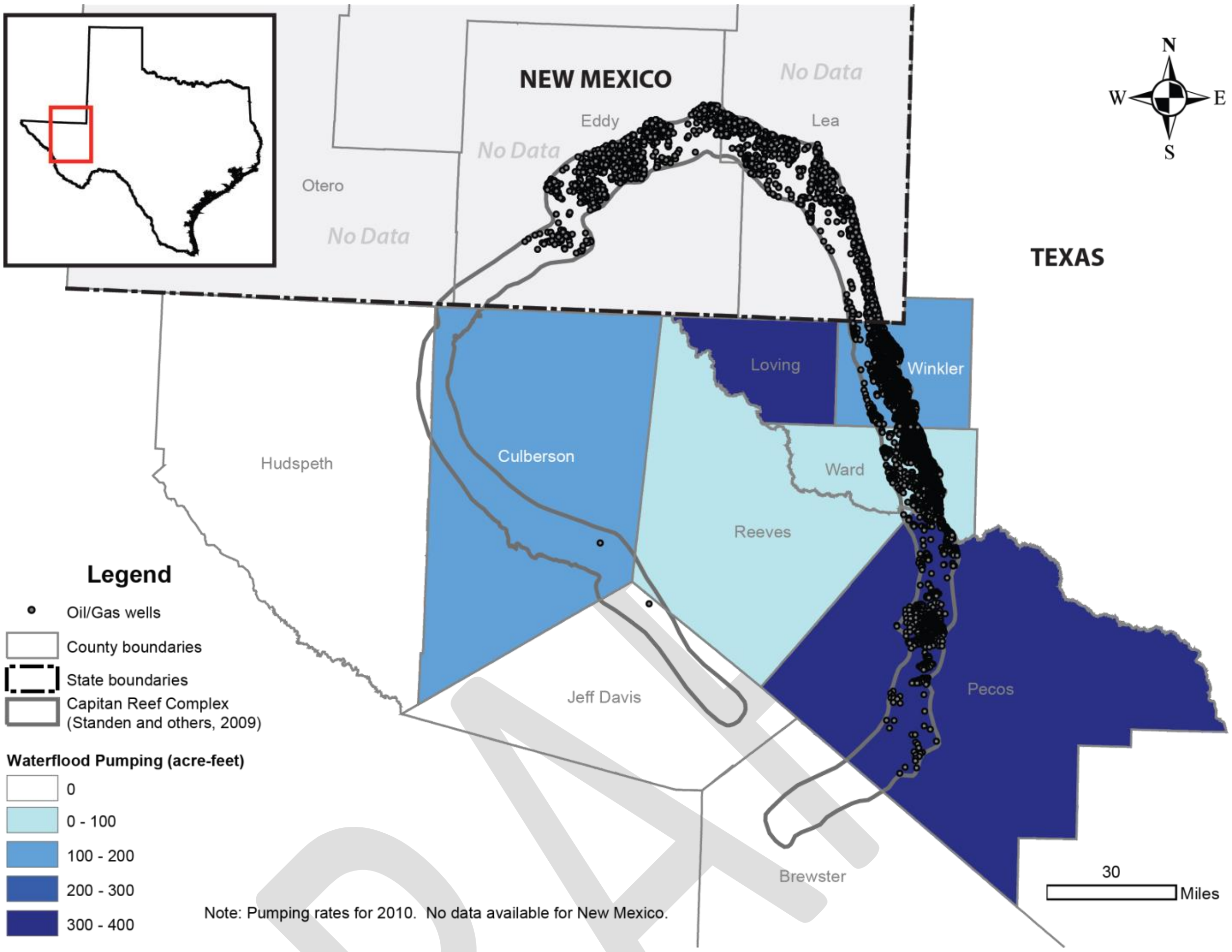
(A)

Figure 4.6.3 Petroleum-related pumping in counties adjacent to the Capitan Reef Complex Aquifer from Nicot and others (2011; 2012). This pumping falls under five categories: (A) tight-formation completion, (B) enhanced oil recovery, (C) waterflooding, (D) drilling, and (E) hydraulic fracturing consumption.



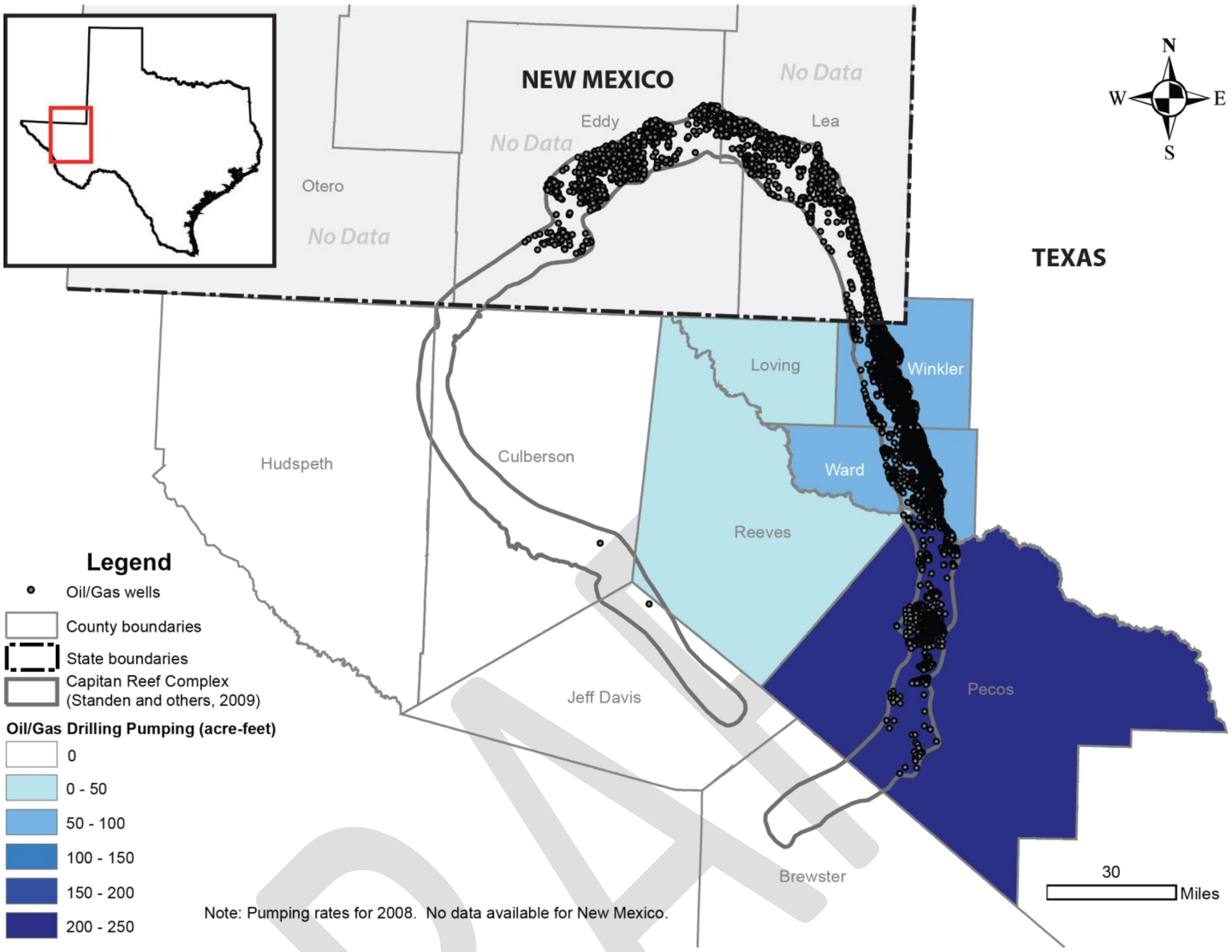
(B)

Figure 4.6.3 (continued).



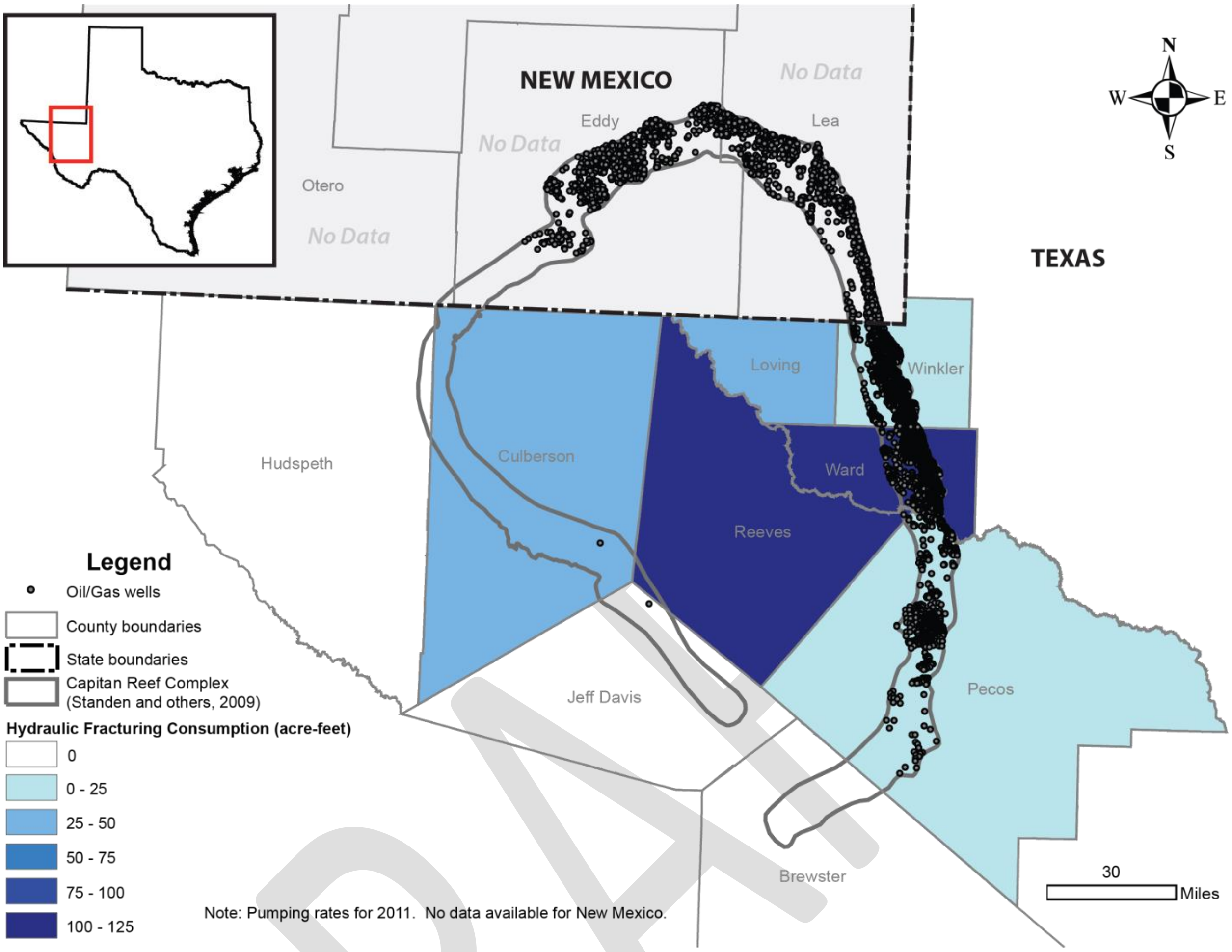
(C)

Figure 4.6.3 (continued).



(D)

Figure 4.6.3 (continued).



(E)

Figure 4.6.3 (continued).

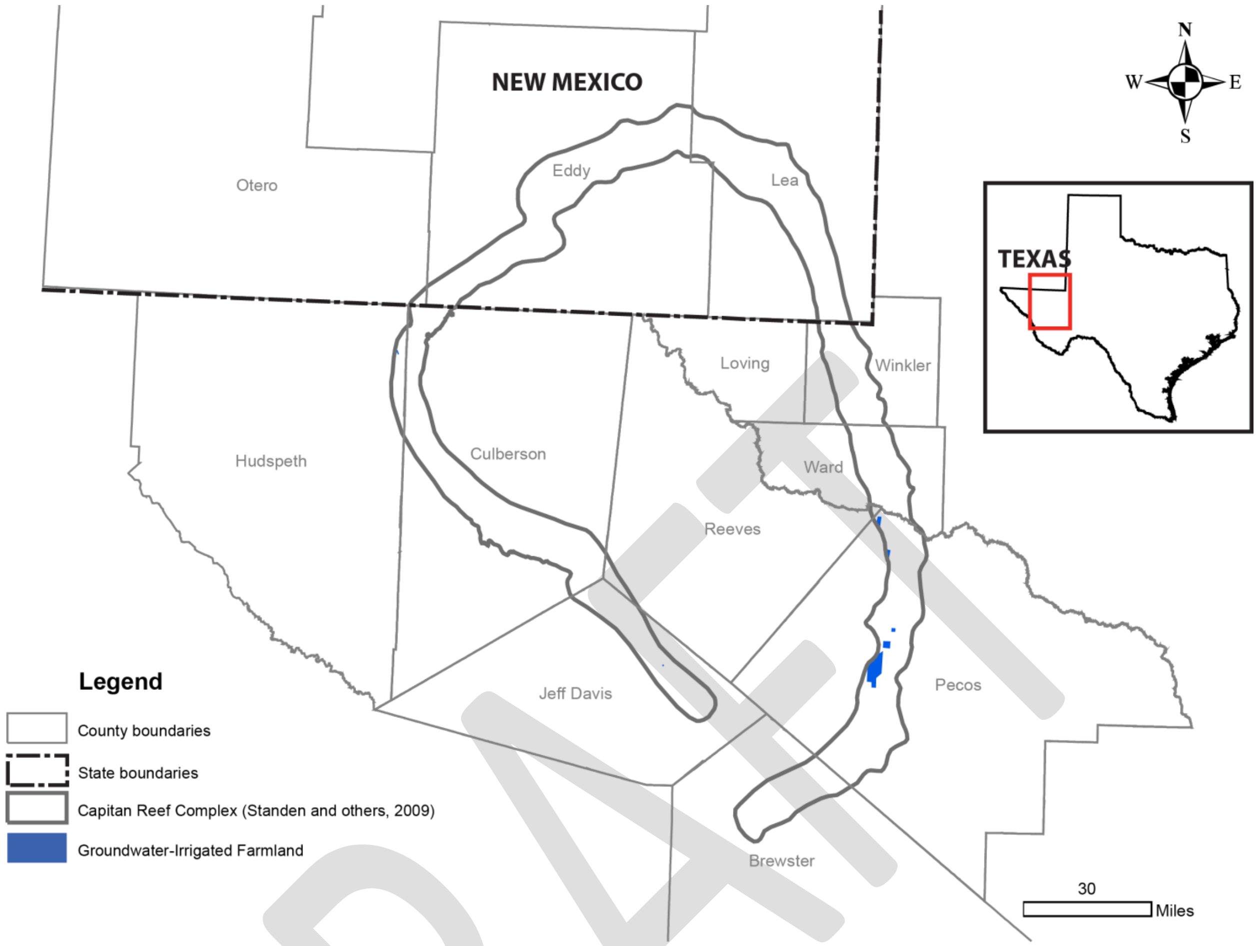
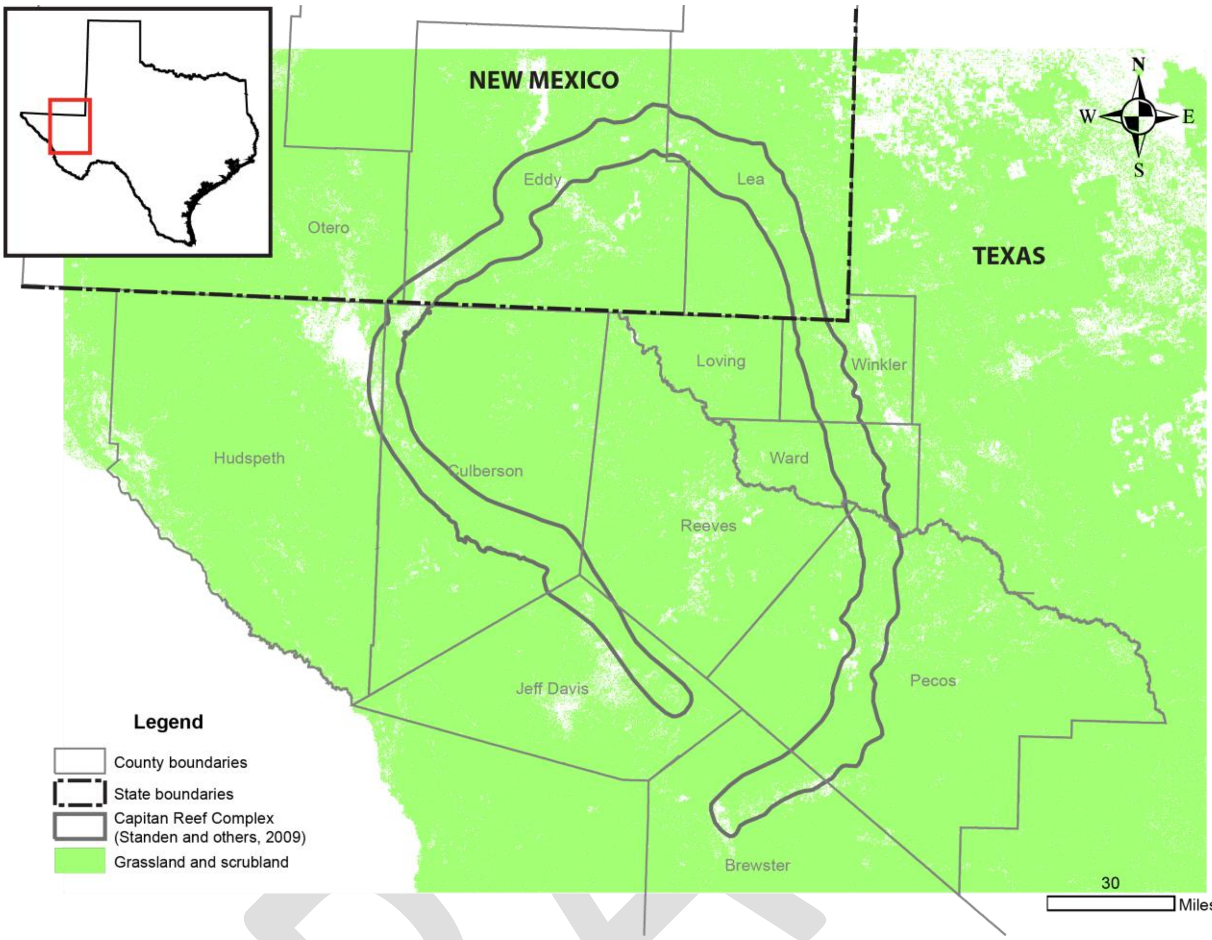
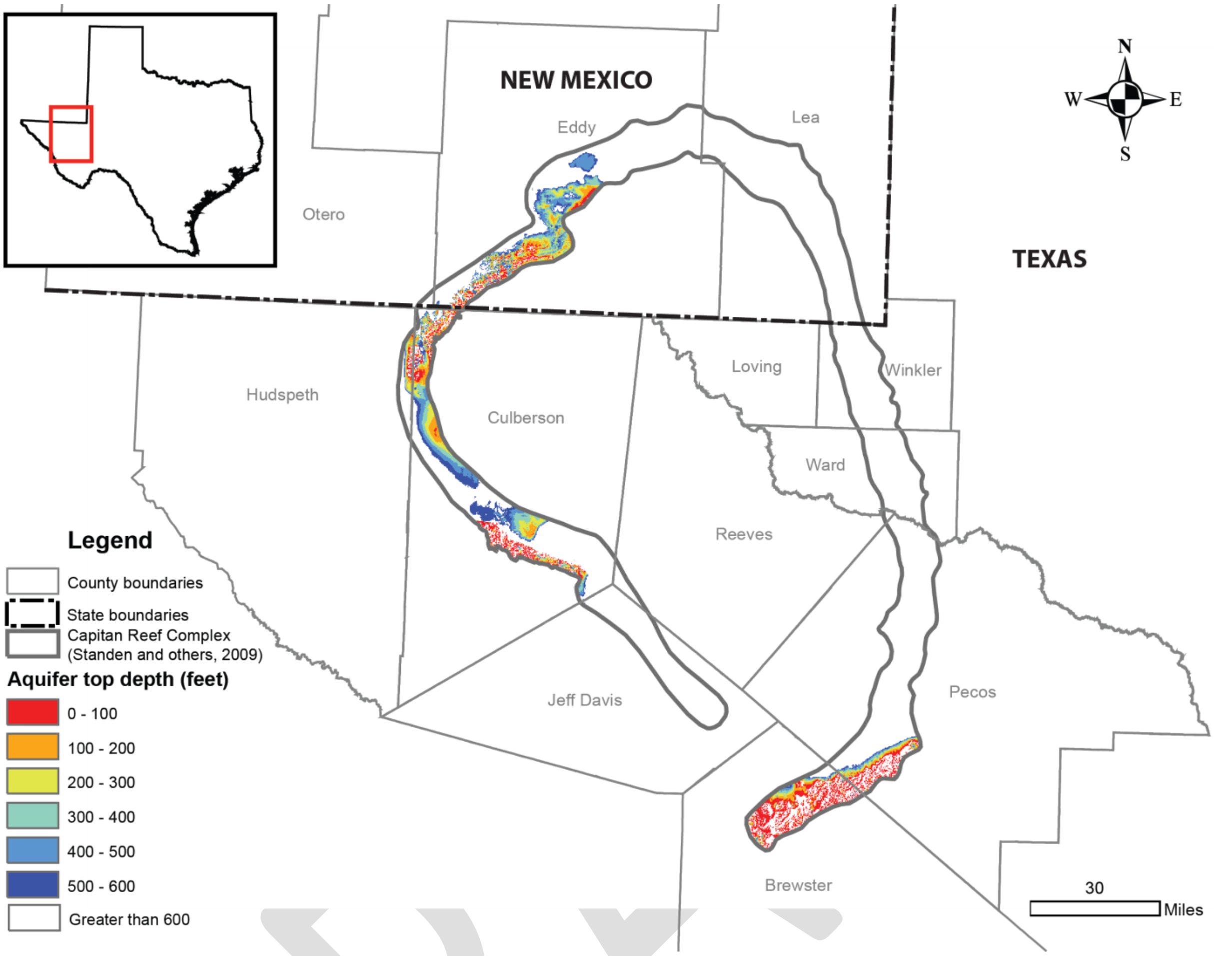


Figure 4.6.4 Spatial distribution of groundwater-irrigated farmland overlying the Capitan Reef Complex Aquifer.



(A)

Figure 4.6.5 The spatial distribution of livestock pumping (A) based grassland and scrubland land cover from the National Land Cover Dataset throughout the study area (Vogelman and others, 1998a; 1998b) and (B) the portion of the Capitan Reef Complex Aquifer that would potentially be used for livestock pumping based on the combination of depth to the top of the aquifer and an average Capitan Reef Complex Aquifer livestock well depth of 600 feet. Livestock pumping will be distributed in model cells that include the shallow zones in (Figure 4.6.5B).



(B)

Figure 4.6.5 (continued).

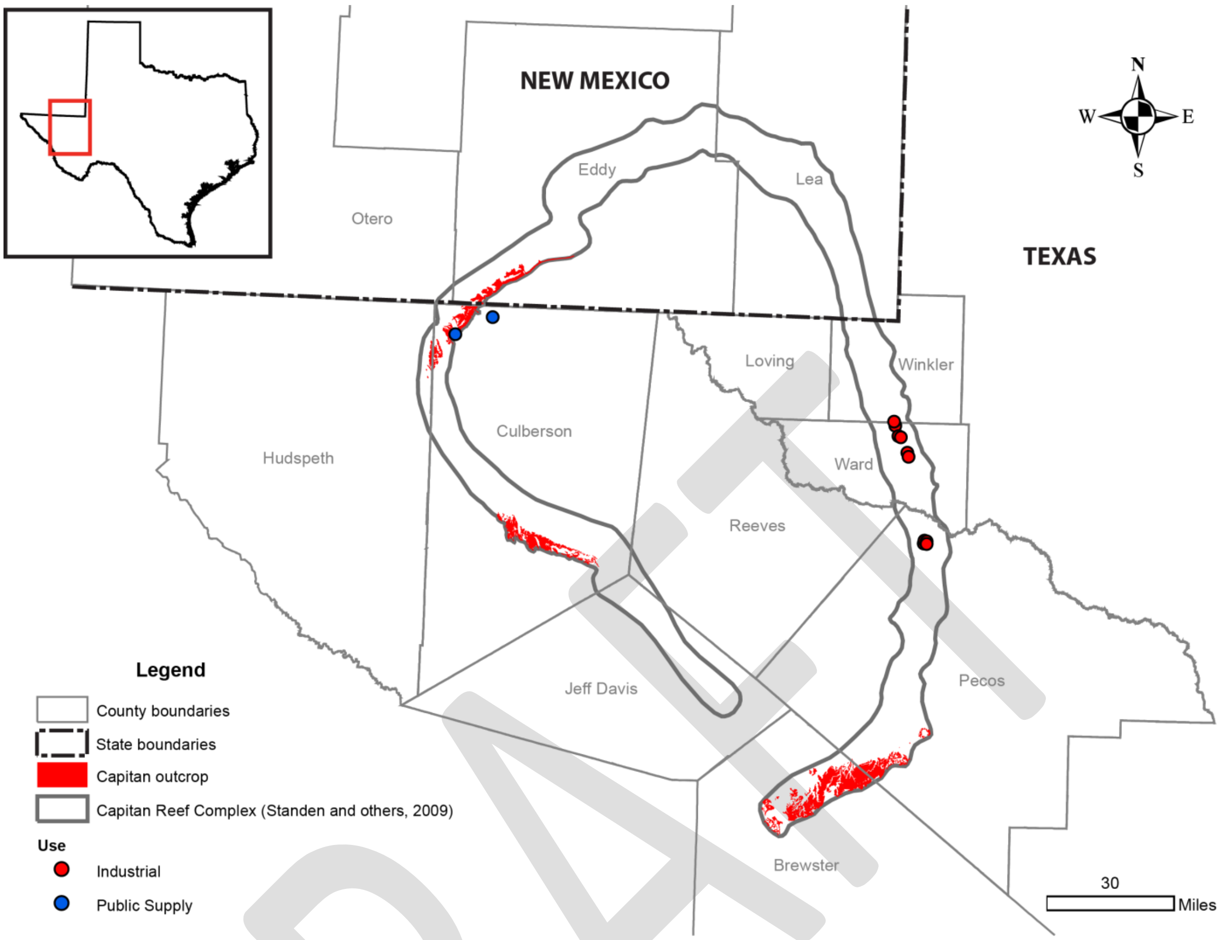
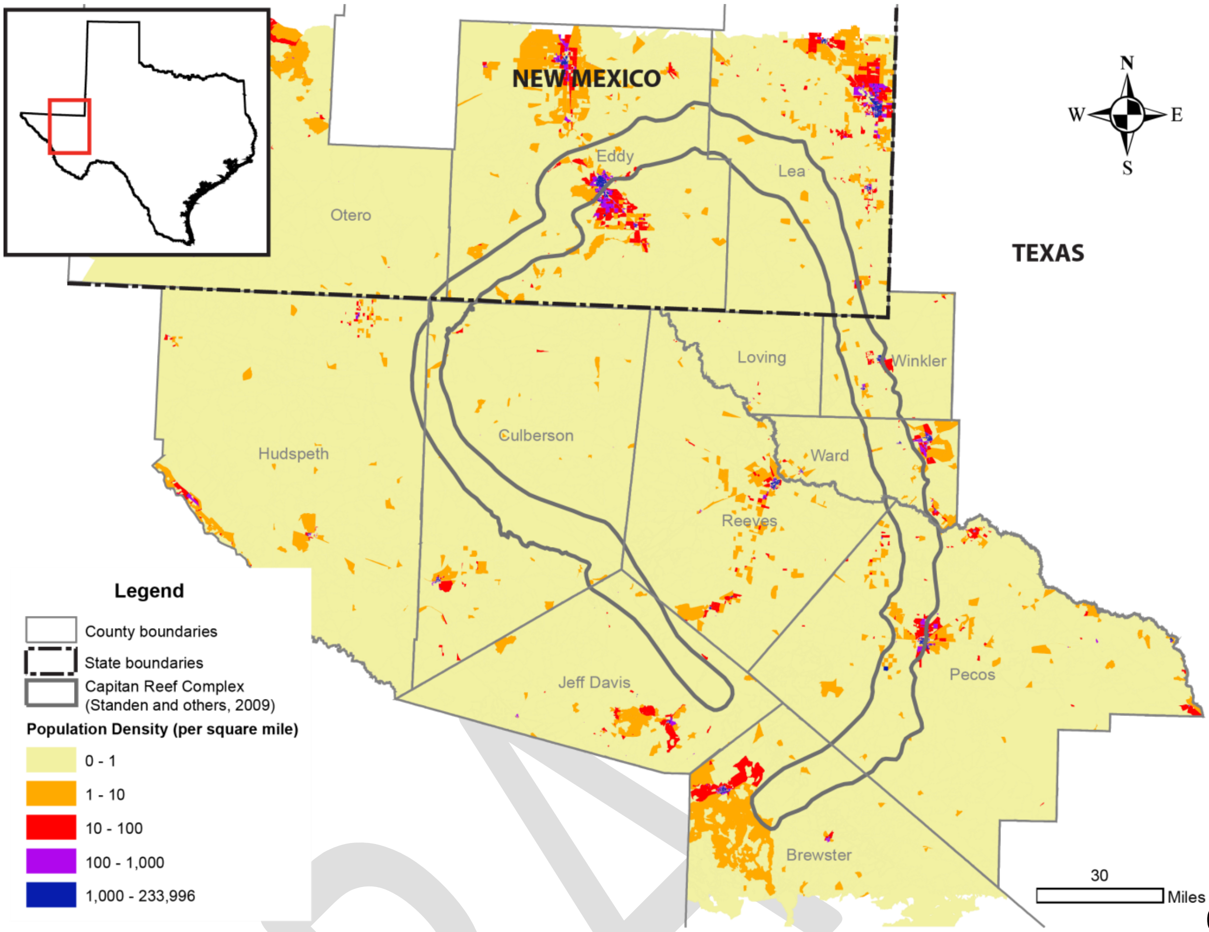
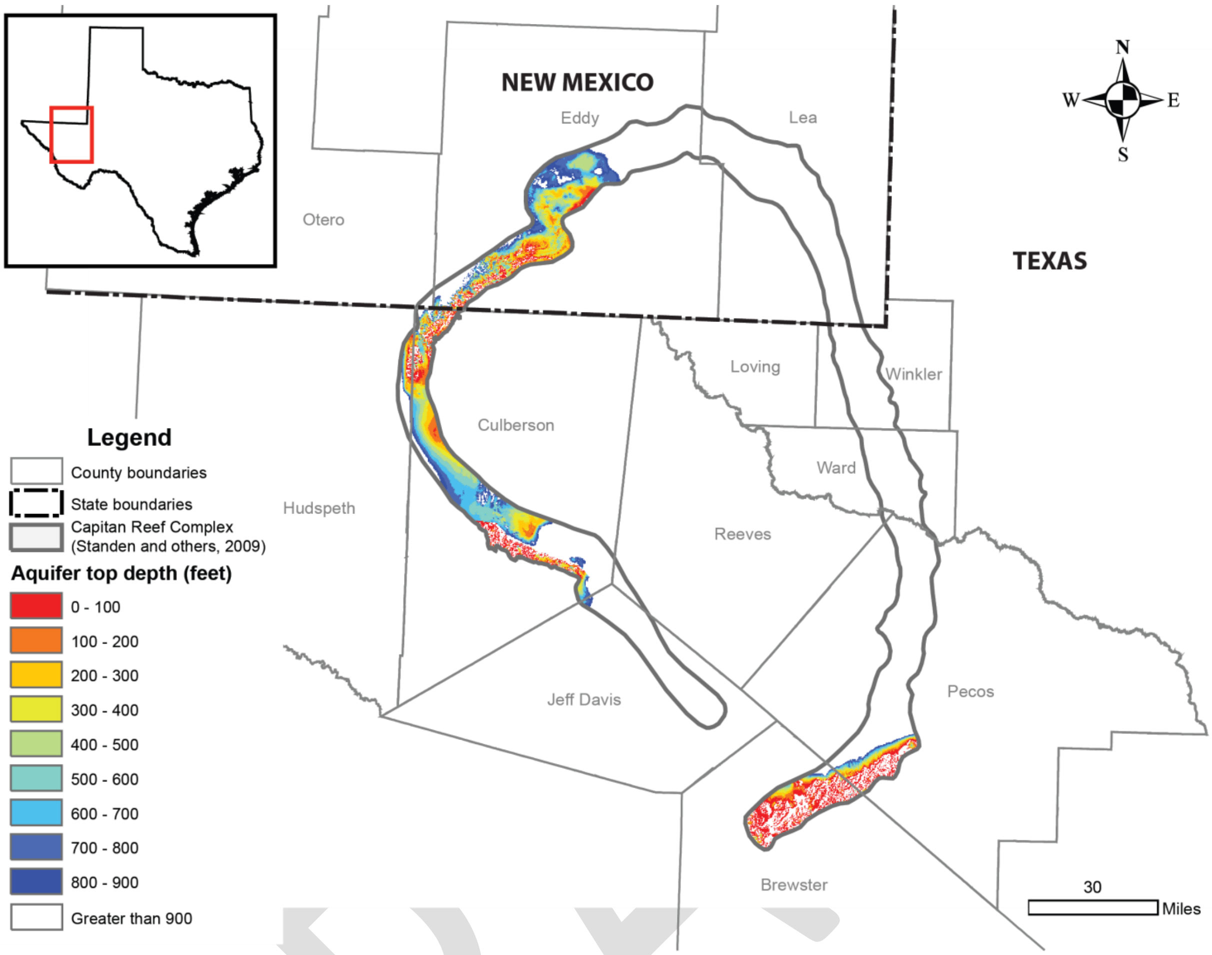


Figure 4.6.6 The spatial distribution of manufacturing (industrial) and municipal (public supply) pumping. Manufacturing and public supply pumping will be distributed in model cells that coincide with the well locations.



(A)

Figure 4.6.7 Population density in the Capitan Reef Complex Aquifer study area (A). Rural domestic pumping in the Capitan Reef Complex Aquifer is distributed based on the rural population over the aquifer and the combination of depth to the top of the aquifer and an average Capitan Reef Complex Aquifer domestic well depth of 900 feet (B). Rural domestic pumping will be distributed in model cells that include the shallow zones in (Figure 4.6.7B).



(B)

Figure 4.6.7 (continued).

4.7 Water Quality

The Capitan Reef Complex Aquifer generally has slightly to very saline groundwater (Brown, 1997).

4.7.1 Major Elements

In some parts of the Capitan Reef Complex Aquifer, concentrations of total dissolved solids, chloride, fluoride, and sulfate exceed applicable water quality standards. High concentrations of these constituents occur in both eastern and western parts of the aquifer in Texas, with especially high concentrations occurring in Pecos, Ward, and Winkler counties (Brown, 1997). Iron and manganese concentrations exceeding their respective water quality standards occur in the western extent of the aquifer.

Figure 4.7.1 shows total dissolved solids concentrations in Capitan Reef Complex Aquifer groundwater. The occurrence of fresh groundwater—total dissolved solids less than 1,000 milligrams per liter—is restricted to aquifer outcrops in Brewster, Culberson, Hudspeth, and

Pecos counties. In areas where the Capitan Reef Complex Aquifer occurs at depth, groundwater is slightly to very saline with a range of total dissolved solids of 1,000 milligrams per liter to greater than 10,000 milligrams per liter. The most saline groundwater occurs in northern Pecos County and Ward County. Groundwater salinity generally increases as groundwater flows away from the outcrops where recharge occurs, reaching a maximum in the deepest parts of the aquifer.

Groundwater in the Capitan Reef Complex Aquifer displays a wide range of geochemical compositions (Figure 4.7.2). Groundwater compositions range from calcium-magnesium to sodium compositions and bicarbonate to sulfate to chloride compositions. These compositional ranges represent geochemical processes that take place as the groundwater flows through the aquifer interacting with aquifer rock and mixing with groundwater inflows from surrounding stratigraphic units (Figure 4.7.3). These compositions indicate groundwater interaction with calcite, dolomite, gypsum, and halite, minerals that occur within the Capitan Reef Complex and adjacent stratigraphic units. Groundwater interaction with dolomite and calcite would produce calcium-magnesium-bicarbonate compositions, gypsum would produce calcium-sulfate compositions, and halite would produce sodium-chloride compositions. In the Capitan Reef Complex Aquifer, groundwater with calcium-magnesium-bicarbonate compositions occur in or adjacent to Capitan Reef Complex outcrops in the Guadalupe and Glass mountains. Groundwater with calcium-magnesium-sulfate compositions occur in deeper parts of the aquifer in northern Pecos County while calcium-sulfate groundwater compositions occur adjacent to the Delaware Mountains in Culberson County. Capitan Reef Complex Aquifer groundwater with sodium-chloride compositions are associated with some of the most saline groundwater in the aquifer—occurring in Ward County. Figure 4.7.4 shows changes in groundwater composition that take place along a Capitan Reef Complex Aquifer flow path extending from Brewster County, north through Pecos County to Ward and Winkler counties (Figure 4.7.1). As the groundwater flows northward, it changes from calcium-magnesium-bicarbonate and calcium-magnesium-sulfate compositions in Brewster County and southern Pecos County to sodium-potassium-chloride compositions in Ward and Winkler counties. This pattern of geochemical composition changes suggests increasing inputs from halite dissolution as the groundwater flows northward.

4.7.2 Isotopes

Groundwater isotopic compositions can provide information about groundwater hydrology. Concentrations of different isotopes often change in response to processes such as evaporation, water-rock interaction, recharge processes, and the elapsed time since recharge.

Groundwater carbon-13 isotopic compositions ($\delta^{13}C$) isotopic compositions represent the ratios of stable carbon isotopes—^{12}C and ^{13}C—in groundwater relative to composition of a standard—PDB calcite (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater carbon-13 isotopic compositions reflect relative carbon inputs from soil and water-rock interaction. Groundwater near recharge zones tend to have more negative carbon-13 compositions reflecting recent contact with the soil. As the groundwater flows through the aquifer—away from the recharge zone—water-rock interaction results in the groundwater taking on more positive carbon-13 isotopic compositions reflecting those of the aquifer rock. This trend is most apparent in the eastern part of the Capitan Reef Complex Aquifer where carbon-13 isotopic compositions range from -10.7 per mil in the aquifer outcrop in Brewster County to -3.6 per mil in northern Pecos County (Figure 4.7.5). Negative groundwater carbon-13 compositions also indicate recharge in the Guadalupe Mountains outcrop but relatively little recharge in the Apache Mountains outcrop of the Capitan Reef Complex. On the other hand, low groundwater carbon-13 compositions in the subsurface adjacent to the southern margin of the Delaware Mountains in Culberson County suggest that recent recharge has occurred there.

Carbon-14 decays over time and, consequently, without a continuous influx of carbon-14 with recharge, the carbon-14 activity in groundwater will decrease over time. The result typically is that groundwater carbon-14 activity is higher in shallower parts of an aquifer where recharge is occurring. In the Capitan Reef Complex Aquifer, carbon-14 activity is generally highest—up to 100 percent modern carbon—where the aquifer crops out and recharge occurs, and lowest in the subcrop where there is no recharge and almost all of the groundwater carbon-14 has decayed (Figure 4.7.6). This figure shows the trend of decreasing groundwater carbon-14 activity northwards from the Glass Mountains outcrop of Brewster County and southern Pecos County. The spatial distribution of carbon-14 activity in the Capitan Reef Complex Aquifer suggest that recharge zones occur in the aquifer outcrops in the Guadalupe and Glass mountains, and near the southern margin of the Delaware Mountains, while there is little recharge in the Apache Mountains outcrop—as suggested by groundwater carbon-13.

Groundwater tritium behaves like carbon-14 except that it has a faster decay rate with a half-life of 12.3 years compared to 5,730 years for carbon-14 (Clark and Fritz, 1997). High tritium activity indicate the most recent recharge. In the Capitan Reef Complex Aquifer, the groundwater tritium activity ranges between 0 and 5 Tritium Units (Figure 4.7.7). However, except for a well in Culberson County with tritium activity in excess of 4 Tritium Units, most groundwater tritium activity is 0.1 Tritium Units or less. This indicates that there is very little recent recharge to the aquifer. This most recent recharge is limited to an area near the southern margin of the Delaware Mountains.

Groundwater stable hydrogen ($\delta^{2}H$) and oxygen ($\delta^{18}O$) isotopic compositions represent the ratios of stable hydrogen isotopes—H and ^{2}H—and stable oxygen isotopes—^{16}O and ^{18}O—in groundwater relative to composition of standard mean ocean water (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater stable hydrogen ($\delta^{2}H$) and oxygen ($\delta^{18}O$) isotopic compositions reflect the composition of the precipitation that recharged the aquifer. Consequently, the hydrogen and oxygen isotopic compositions of groundwater can be used as an indicator of the conditions under which recharge to the aquifer occurred. Figures 4.7.8 and 4.7.9 show groundwater hydrogen and oxygen isotopic compositions in the Capitan Reef Complex Aquifer. Groundwater stable hydrogen and oxygen isotopic compositions in the Capitan Reef Complex Aquifer lie in the ranges -71 to -43 per mil and -10 to -7 per mil, respectively. There are no apparent isotopic composition trends along groundwater flowpaths. The well located adjacent to the southern margin of the Delaware Mountains that is associated with recent recharge based on its groundwater carbon-13, carbon-14, and tritium compositions also has stable hydrogen and oxygen isotopic compositions that are more distinct—much higher—than other locations in the Capitan Reef Complex Aquifer. Stable hydrogen and oxygen isotope compositions generally lie along the Global Meteoric Water Line—the average relationship between stable hydrogen and oxygen isotopic compositions in precipitation around the World (Craig, 1961). Figure 4.7.10 shows Capitan Reef Complex Aquifer groundwater stable hydrogen and oxygen isotopic compositions relative to the Global Meteoric Water Line. The lowest stable hydrogen and oxygen groundwater isotopic compositions occur in the Guadalupe, Apache, and Glass mountains (Figures 4.7.8 and 4.7.9). The highest stable hydrogen and oxygen groundwater isotopic compositions occur just south of the Delaware Mountains. The range of groundwater stable hydrogen and oxygen isotopic compositions is narrower in the eastern arm of the Capitan Reef Complex Aquifer—Brewster, Pecos, Ward, and Winkler counties—than in the west—Culberson and Hudspeth counties (Figure 4.7.11).

4.7.3 Implications for Recharge Based on Groundwater Isotopic Compositions

The range of stable hydrogen and oxygen isotopic compositions can be influenced by temperature, altitude, amount of precipitation, and water-rock interaction effects (Dansgaard, 1964; Fontes and Olivry, 1977; Scholl and others, 1996; Gonfiantini, 1985; Fontes, 1980). The most likely effects influencing the range of groundwater stable hydrogen and oxygen isotopic compositions in the Capitan Reef Complex Aquifer are the altitude and amount effects. The altitude effect would result in recharge taking place at higher elevations—such as in the Guadalupe Mountains—resulting in groundwater with lower stable hydrogen and oxygen isotopic compositions. Conversely, recharge occurring at lower elevations would be characterized by higher stable hydrogen and oxygen isotopic compositions. Higher precipitation amounts produce more negative isotopic compositions in the precipitation and resultant groundwater. Note that more precipitation also occurs at higher elevations—such as the Guadalupe Mountains—consequently it would be difficult to differentiate between the impacts of the amount and elevation effects on groundwater stable hydrogen and oxygen isotopic compositions (Figure 2.1.6). The influence of these two effects can explain the difference in the ranges of groundwater stable hydrogen and oxygen isotopic compositions observed in the eastern and western arms of the Capitan Reef Complex Aquifer. The narrower range of groundwater stable hydrogen and oxygen isotope compositions in the eastern arm of the Capitan Reef Complex Aquifer can be explained as representative of a single recharge zone in the outcrops in the Glass Mountains. The wider range of compositions in western side of the Capitan Reef Complex Aquifer—Culberson and Hudspeth counties—represent recharge under a range of conditions of climate and elevation. The relatively low groundwater stable hydrogen and oxygen compositions in northern Culberson County and Hudspeth County can be attributed to recharge in or adjacent to the Guadalupe Mountains—the highest mountains in Texas (Figure 4.7.12). The wide range of groundwater compositions in southern Culberson County represent a wide range of recharge conditions varying from recharge at higher elevations in the Apache Mountains—the lowest values—to recharge taking place at lower elevations in the valley between the Apache and Delaware mountains—the higher values (Figure 4.7.12).

An alternative explanation for the highest groundwater stable hydrogen and oxygen isotopic compositions in the western arm of the Capitan Reef Complex Aquifer is recent recharge in a climate that is warmer and drier than Pleistocene climate—a pattern that has been observed in other aquifers in the region (Darling, 1997). This explanation is supported by the carbon-14 and tritium data. These data indicate that about half of the groundwater samples collected from the Capitan Reef Complex Aquifer have apparent ages in excess of 10,000 years—carbon-14 of less than 25 percent modern carbon—suggesting recharge during the Pleistocene. Most groundwater carbon-14 apparent ages are in excess of 5,000 years. The highest groundwater stable hydrogen and oxygen isotopic compositions in the western arm of the Capitan Reef Complex Aquifer are associated with very high carbon-14 compositions—approaching 100 percent modern carbon—and the highest tritium concentration, indicating very recent recharge. This groundwater occurs in the subcrop part of the Capitan Reef Complex Aquifer near the southern margin of the Delaware Mountains and is probably the result of rapid recharge down fractures.

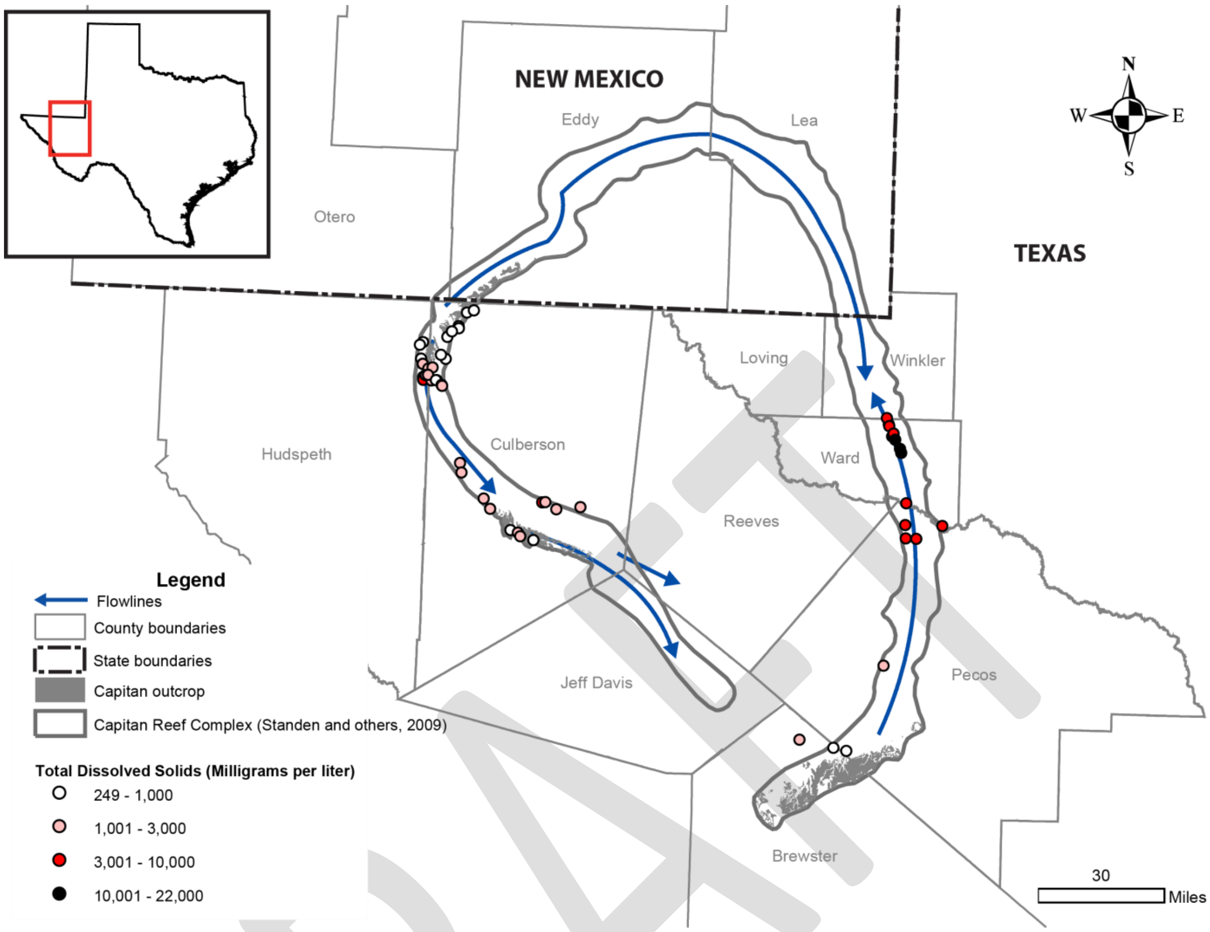


Figure 4.7.1 Total dissolved solids concentration (in milligrams per liter) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

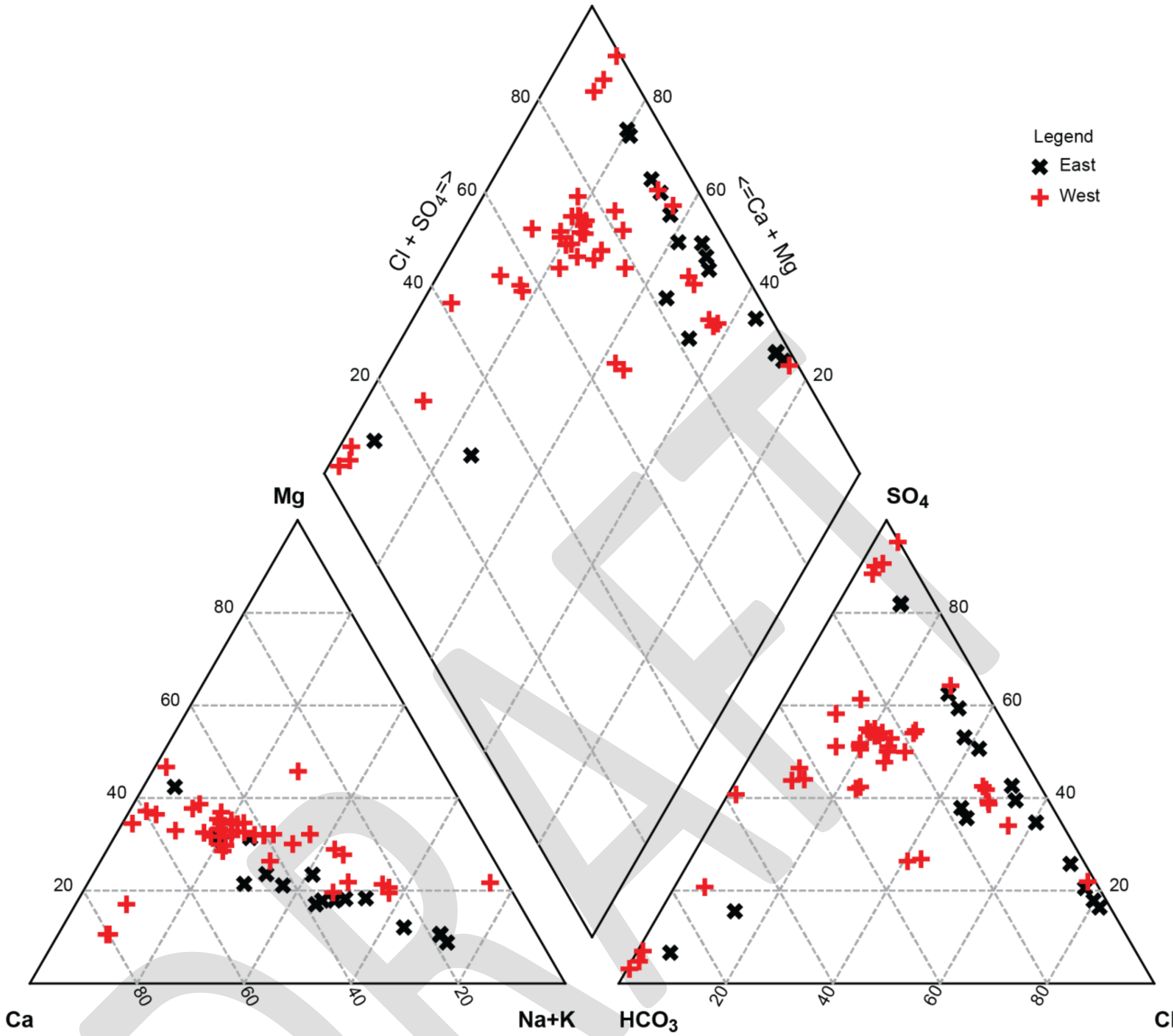


Figure 4.7.2 A Piper diagram showing the range of groundwater compositions in the eastern (Brewster, Pecos, Ward and Winkler counties) and the western (Culberson and Hudspeth counties) parts of the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

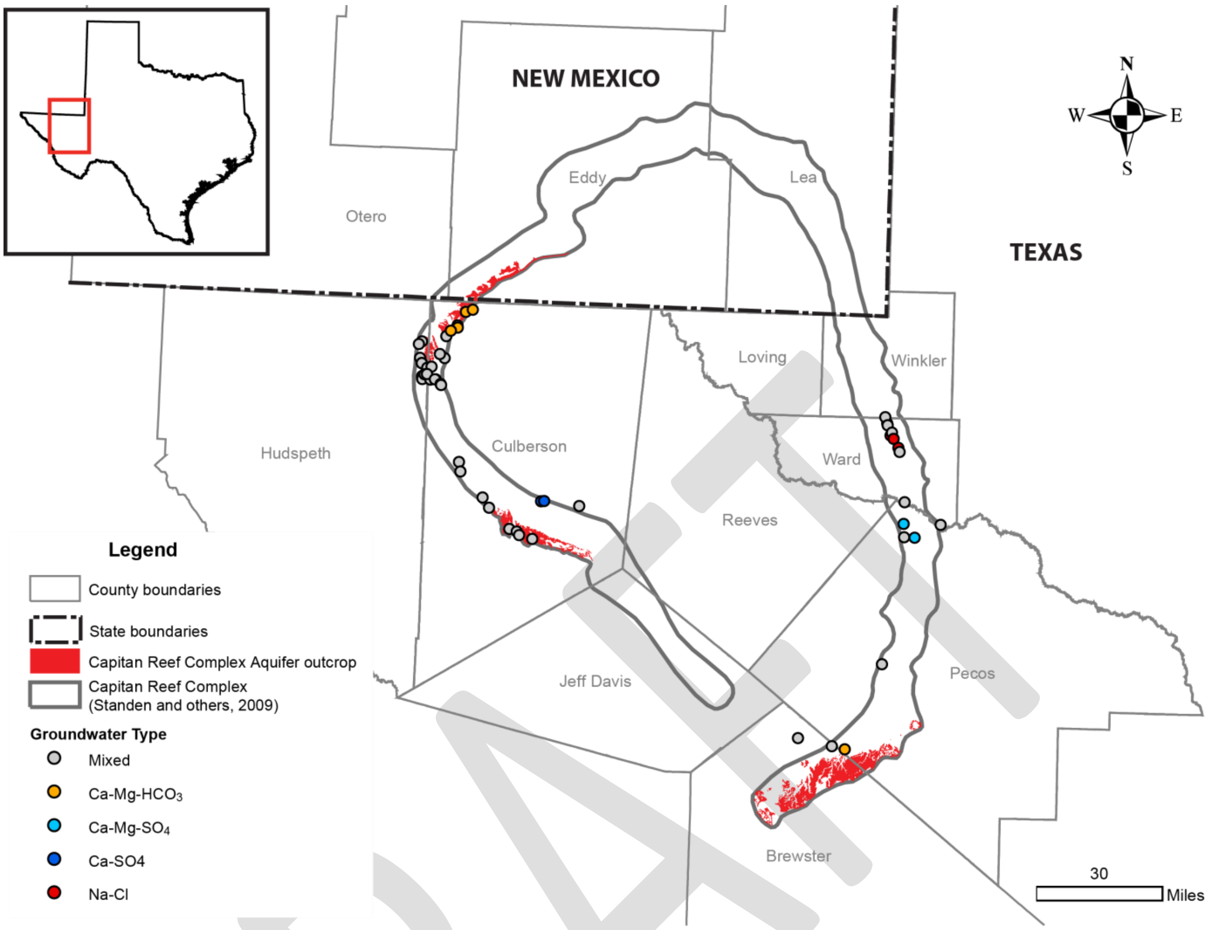


Figure 4.7.3 Groundwater types in the Capitan Reef Complex Aquifer (data from Texas Water Development Board, 2012b.

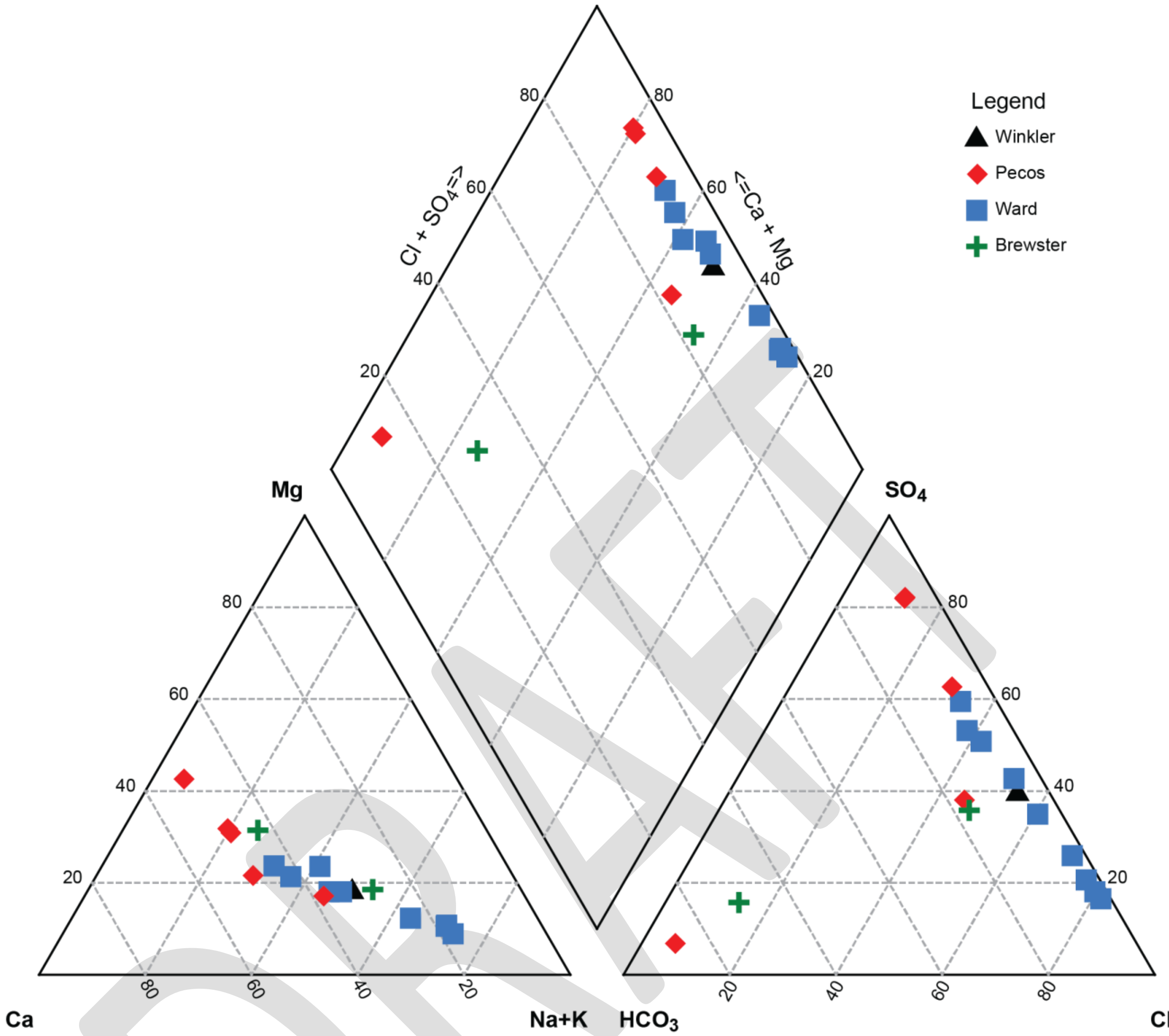


Figure 4.7.4 A Piper diagram showing the range of groundwater compositions in counties of the eastern (Brewster, Pecos, Ward, and Winkler counties) part of the Capitan Reef Complex Aquifer.

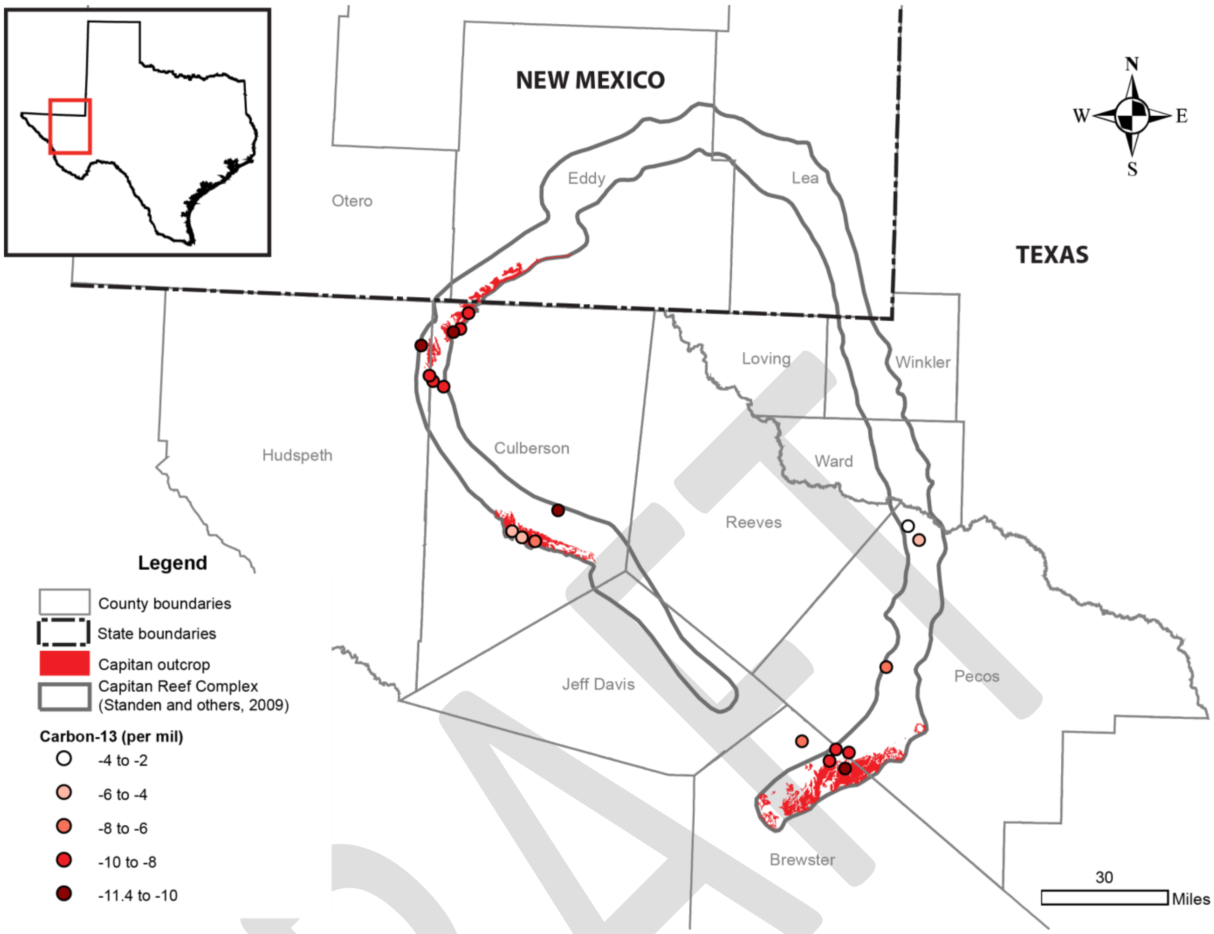


Figure 4.7.5 Groundwater Carbon-13 isotopes (in per mil) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

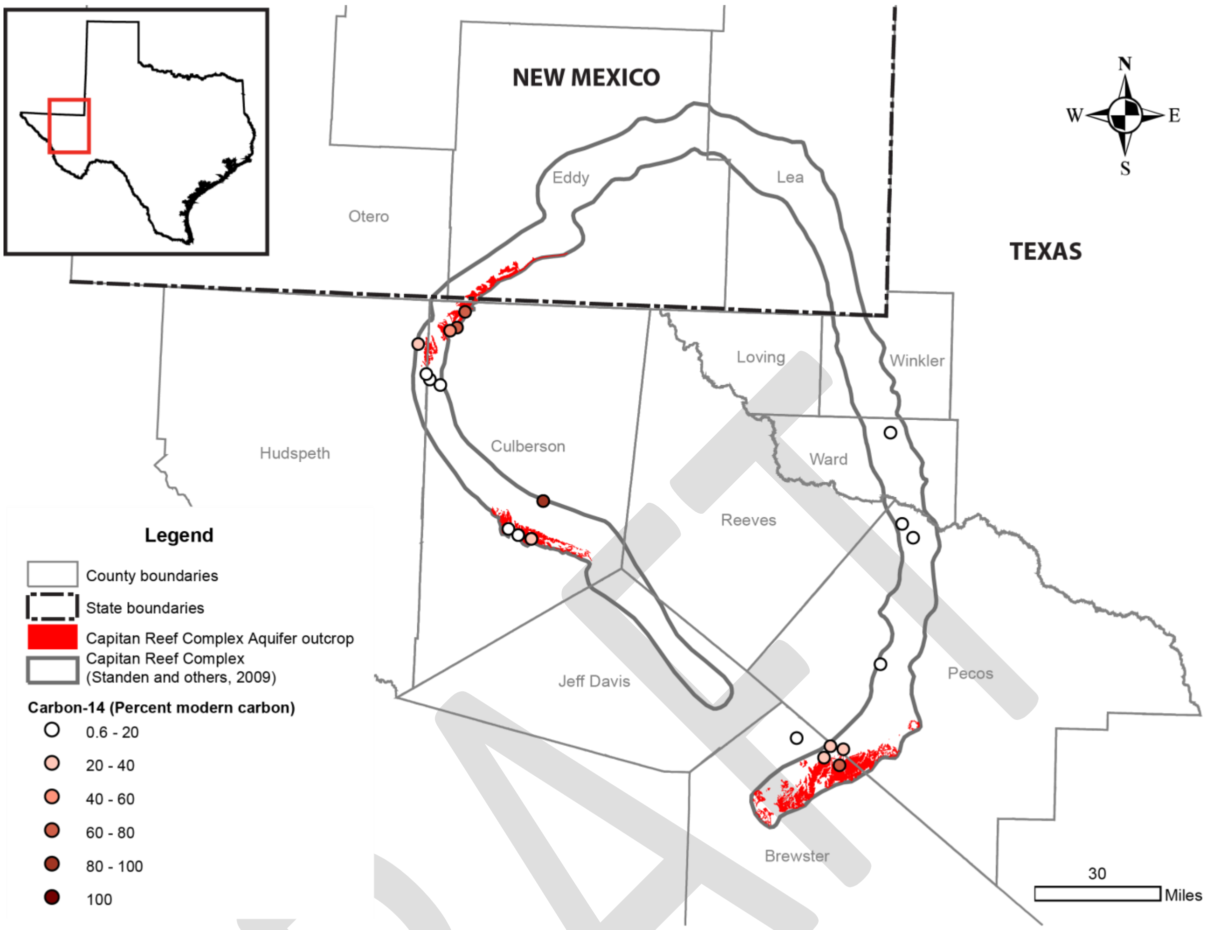


Figure 4.7.6 Groundwater Carbon-14 (in percent modern carbon) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

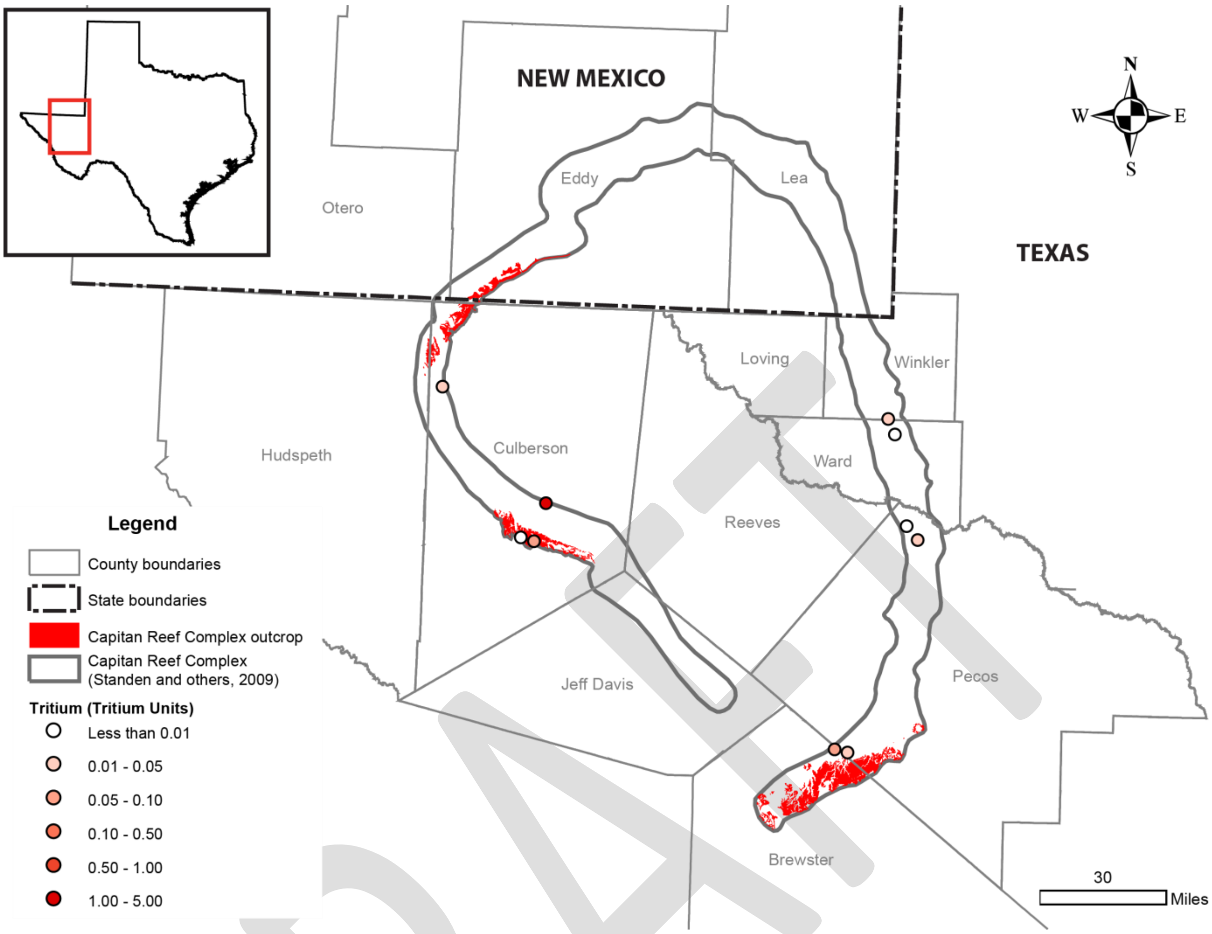


Figure 4.7.7 Groundwater tritium (in Tritium Units) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

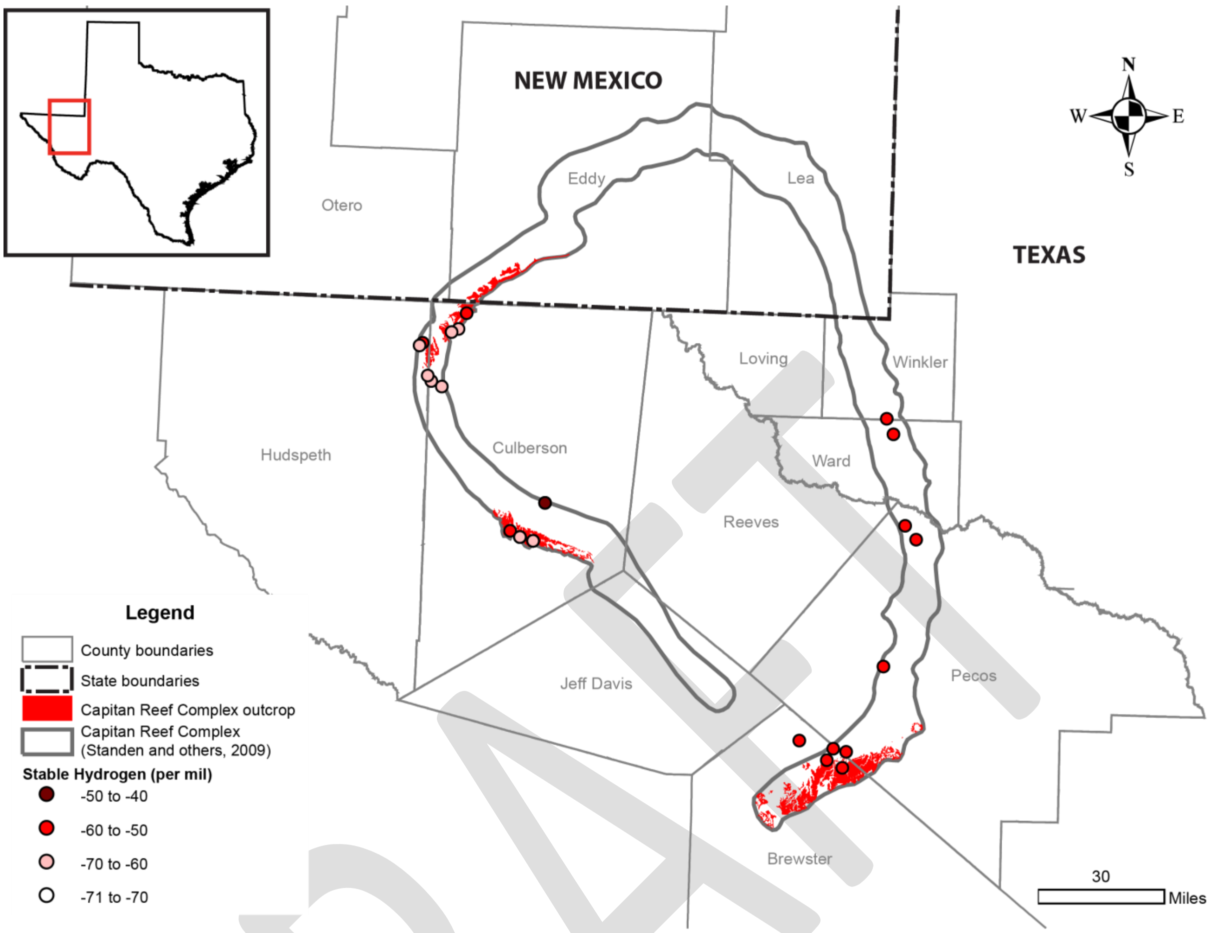


Figure 4.7.8 Groundwater stable hydrogen isotopes (δ^2H, per mil) in the Capitan Reef Complex Aquifer.

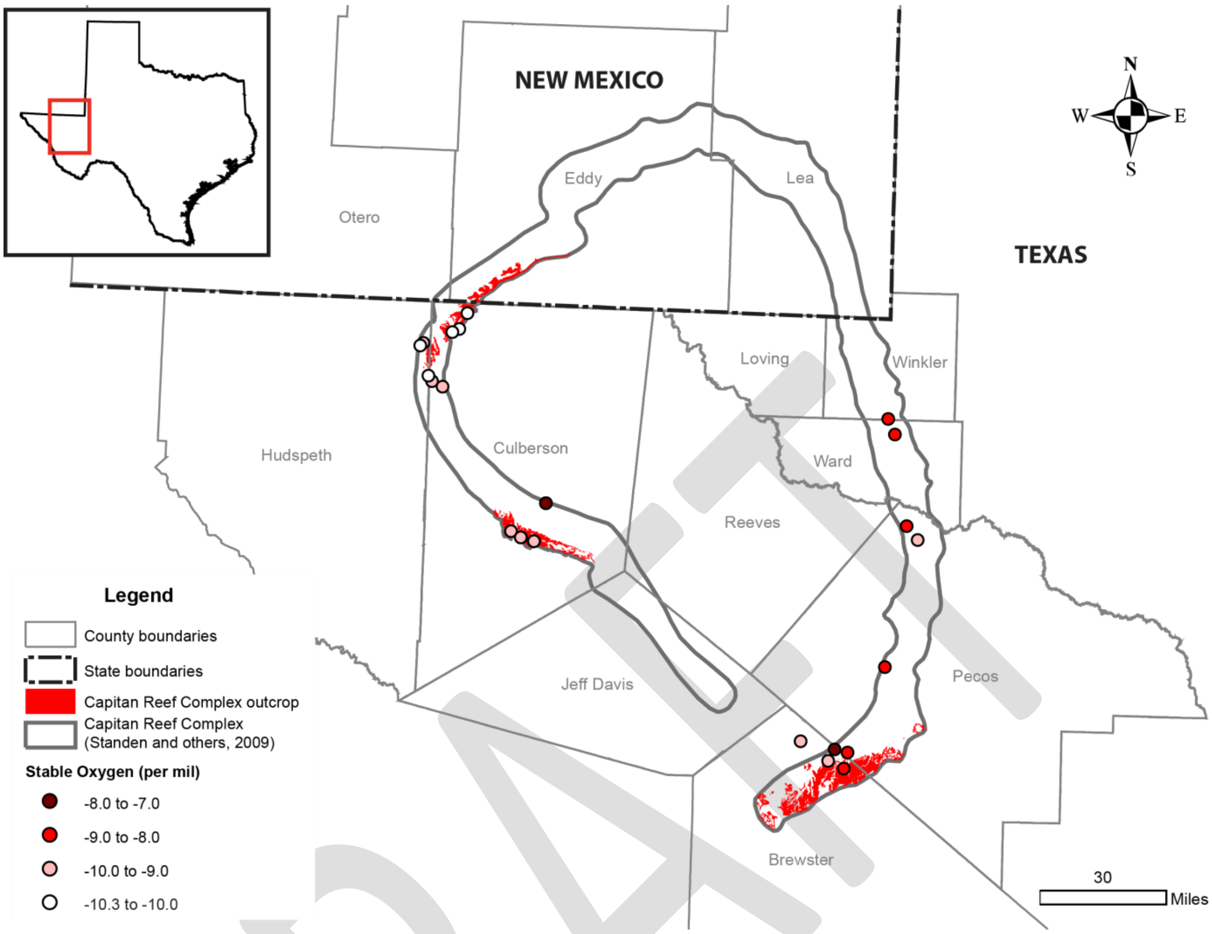


Figure 4.7.9 Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) in the Capitan Reef Complex Aquifer.

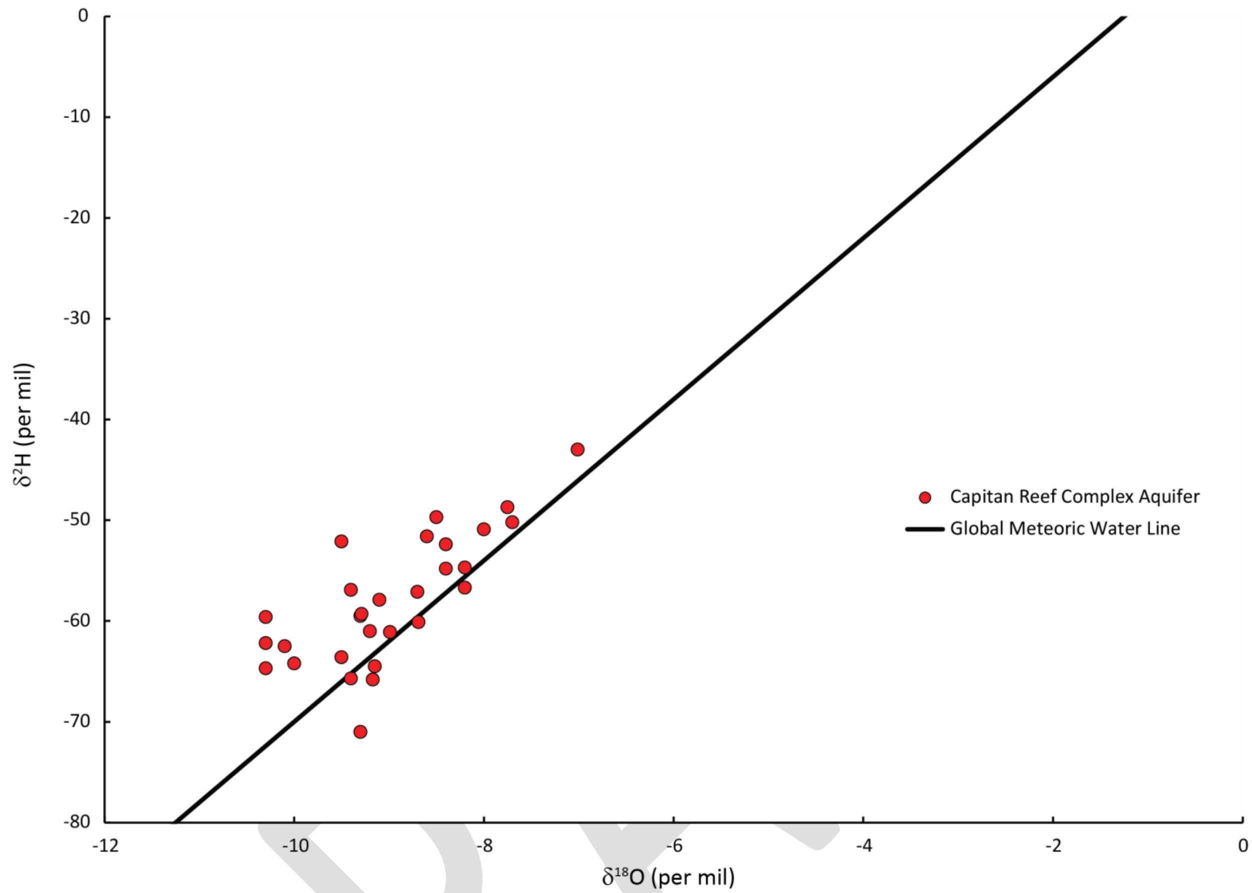


Figure 4.7.10 Capitan Reef Complex Aquifer groundwater stable hydrogen and oxygen isotopes (in per mil) relative to the Global Meteoric Water Line.

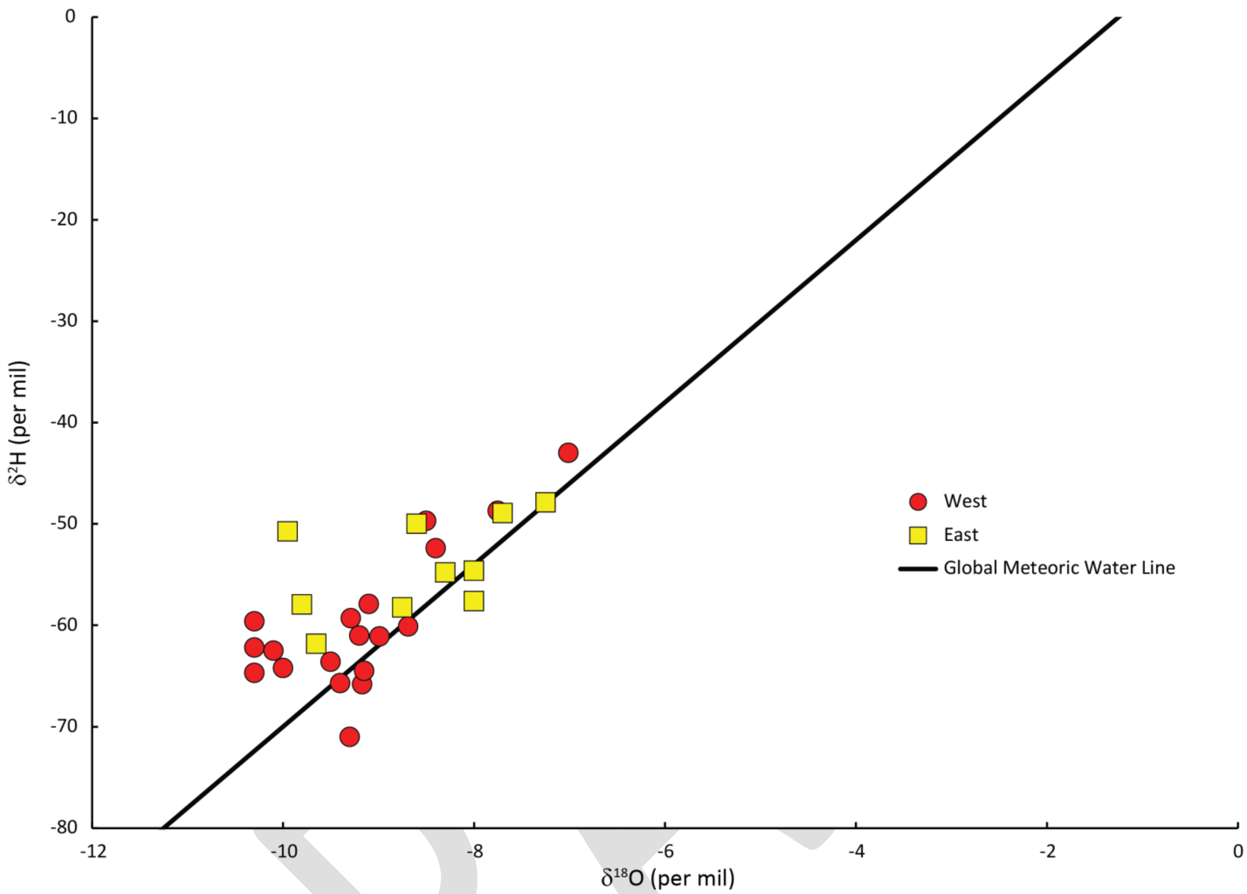


Figure 4.7.11 Comparison of groundwater stable hydrogen and oxygen isotopes (in per mil) in the eastern and western arms of the Capitan Reef Complex Aquifer of Texas.

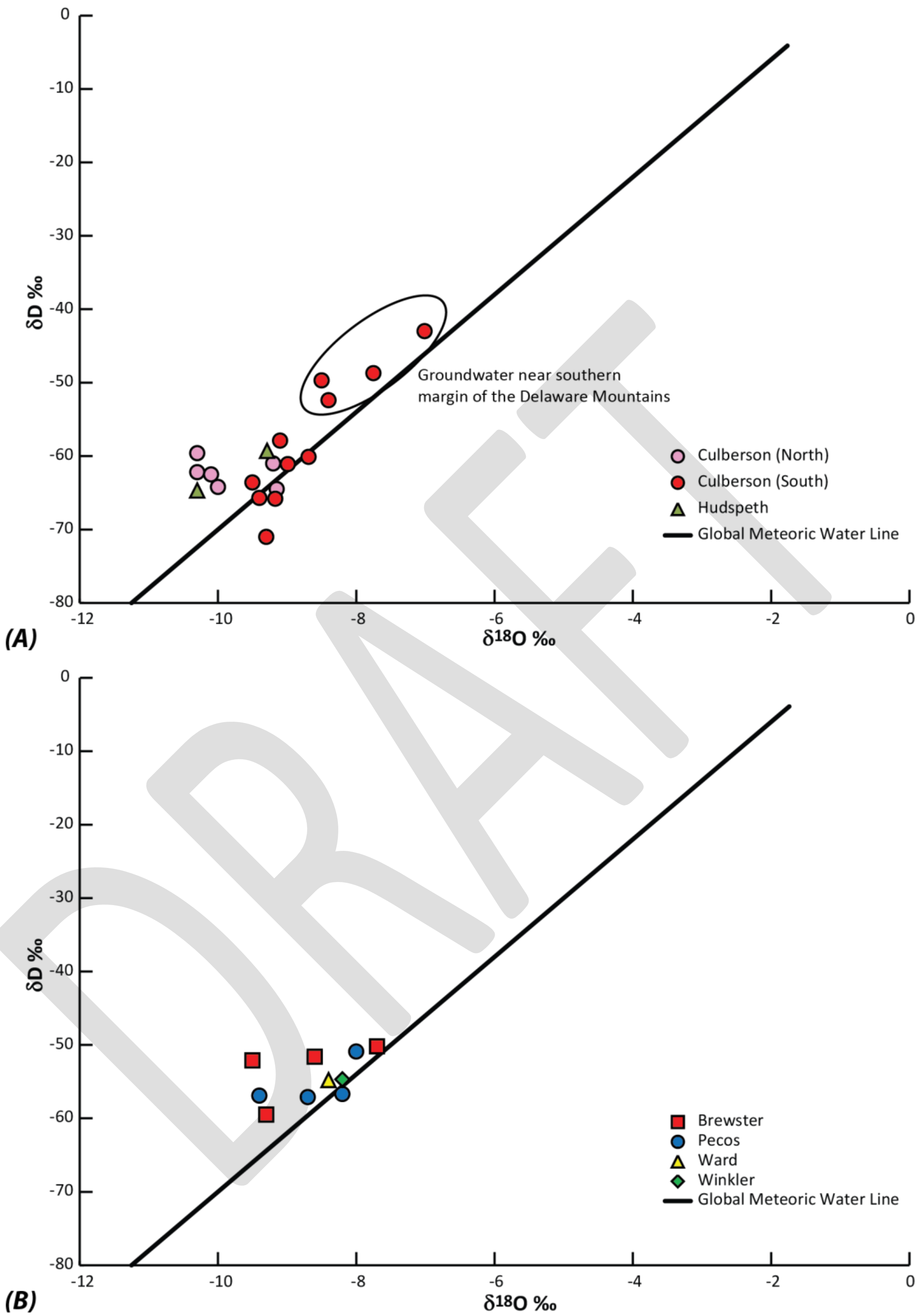


Figure 4.7.12 Comparison of groundwater stable hydrogen and oxygen isotopes (in per mil) in the eastern (A) and western (B) arms of the Capitan Reef Complex Aquifer of Texas by county.

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

The conceptual model of groundwater flow in the eastern arm of the Capitan Reef Complex Aquifer is based on the hydrogeologic setting, described in Section 4.0. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifer. It includes the hydrostratigraphy, hydrogeologic framework, hydraulic properties, hydrologic boundaries, recharge, and discharge. In this study, only the eastern arm of the Capitan Reef Complex Aquifer is included in the conceptual model. The western arm of the Capitan Reef Complex Aquifer was excluded because parts of the western arm are included in the groundwater model of the Bone Spring-Victorio Peak Aquifer by Hutchison (2008).

The Capitan Reef Complex Aquifer is located in the Trans-Pecos region of western Texas and southeastern New Mexico. The boundaries of the Capitan Reef Complex Aquifer used in this study were defined by Standen and others (2009) and differ slightly from the official TWDB boundaries in Brewster County. The Capitan Reef Complex Aquifer is composed of the Capitan Limestone, Carlsbad Limestone, Goat Seep Dolomite, and the Tessey and Vidrio formations (Figure 2.2.3).

The Capitan Reef Complex is bounded—vertically and laterally—by back-reef deposits of the Artesia Group and fore-reef deposits of the Delaware Group and Castile Formation. The Capitan Reef Complex is also overlain by the Salado Formation, a rock salt stratigraphic unit. Where the Salado Formation is absent or thin as a result of dissolution—as is the case in the overlying Monument Draw Trough—the Capitan Reef Complex is overlain by the Rustler Formation (Richey and others, 1985).

Work by Hiss (1976; 1980), Uliana (2001), and Sharp (2001) indicates groundwater flow through the Capitan Reef Complex Aquifer parallel to the reef trend and diverging from the main aquifer outcrops—the Guadalupe, Apache, and Glass mountains (Figure 4.2.1). Groundwater apparently converges in Winkler County. Groundwater in the Capitan Reef Complex Aquifer likely recharges by infiltration of precipitation where the aquifer crops out as noted in Section 4.7 (Figure 5.0.1). Discharge from the Capitan Reef Complex Aquifer likely takes the form of cross-formational flow through overlying aquifers. This is supported by the fact that Capitan Reef Complex Aquifer water levels are generally higher than water levels in overlying aquifers, indicating an upward hydraulic gradient (Section 4.2). It is also possible for the Capitan Reef Complex Aquifer to discharge by cross-formational flow to adjacent fore- and back-reef deposits, especially the back-reef deposits which (1) have higher hydraulic conductivity values than the fore-reef deposits, and (2) there is more evidence of hydrologic connections with the back-reef deposits than the fore-reef deposits (Figure 4.2.2).

In the aquifers overlying the Capitan Reef Complex Aquifer, groundwater flow generally converges on the Monument Draw Trough which coincides with the Capitan Reef Complex

(Figure 5.0.1; Ewing and others, 2008; 2012; Hutchison and others, 2011). Groundwater flow in the surficial Edwards-Trinity (Plateau) and Pecos Valley aquifer also converges on the Pecos River—a major discharge zone for both aquifers (Anaya and Jones, 2009; Hutchison).

The schematic diagram in Figure 5.0.2A is a conceptual block diagram illustrating aquifer contact relationships and sources and sinks of groundwater in the eastern arm of the Capitan Reef Complex Aquifer and overlying aquifers. Constructing the Capitan Reef Complex Aquifer Groundwater Availability Model will require up to five model layers simulating groundwater flow through the Capitan Reef Complex Aquifer and the overlying aquifers and geologic formations within the Monument Draw Trough. The lowermost model layer would represent: (1) the Capitan Reef Complex Aquifer which is exposed at land surface in the Glass Mountains and (2) adjacent parts of the Artesia and Delaware Mountain groups (Figure 5.0.2B). Active cells in the model grid would extend from the Glass Mountains in the south, north to where the Capitan Reef Complex Aquifer intersects with the Pecos River near Carlsbad, New Mexico. Other layers will simulate groundwater flow through the overlying Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers. There is the possibility that additional layers may be used to simulate the Artesia Group, and Salado, and Castile formations that act as confining units. In the eastern arm of the Capitan Reef Complex Aquifer, the Artesia Group pinches out and is absent along the western side of the aquifer. The Salado Formation and possibly the Castile Formation are absent due to dissolution by groundwater discharging from the Capitan Reef Complex Aquifer in northern Pecos County and Winkler and Ward counties resulting in the formation of the Monument Draw Trough through collapse of overlying stratigraphic units and infilling by alluvial and eolian sediments (Figure 4.6.1; Jones, 2001; 2004). In that area, the Capitan Reef Complex Aquifer is in direct contact with the Rustler Aquifer. The Monument Draw Trough collapse structure would facilitate upward discharge that contributes to: (1) saline groundwater discharging from Diamond Y Springs that is located directly over the Capitan Reef Complex Aquifer footprint, and (2) pumping-induced deteriorating groundwater quality observed in the Pecos Valley Aquifer (Veni, 1991; Jones, 2004). An alternative strategy that can be used is to simulate the presence of the confining units is by restricting vertical groundwater flow between the aquifers they separate.

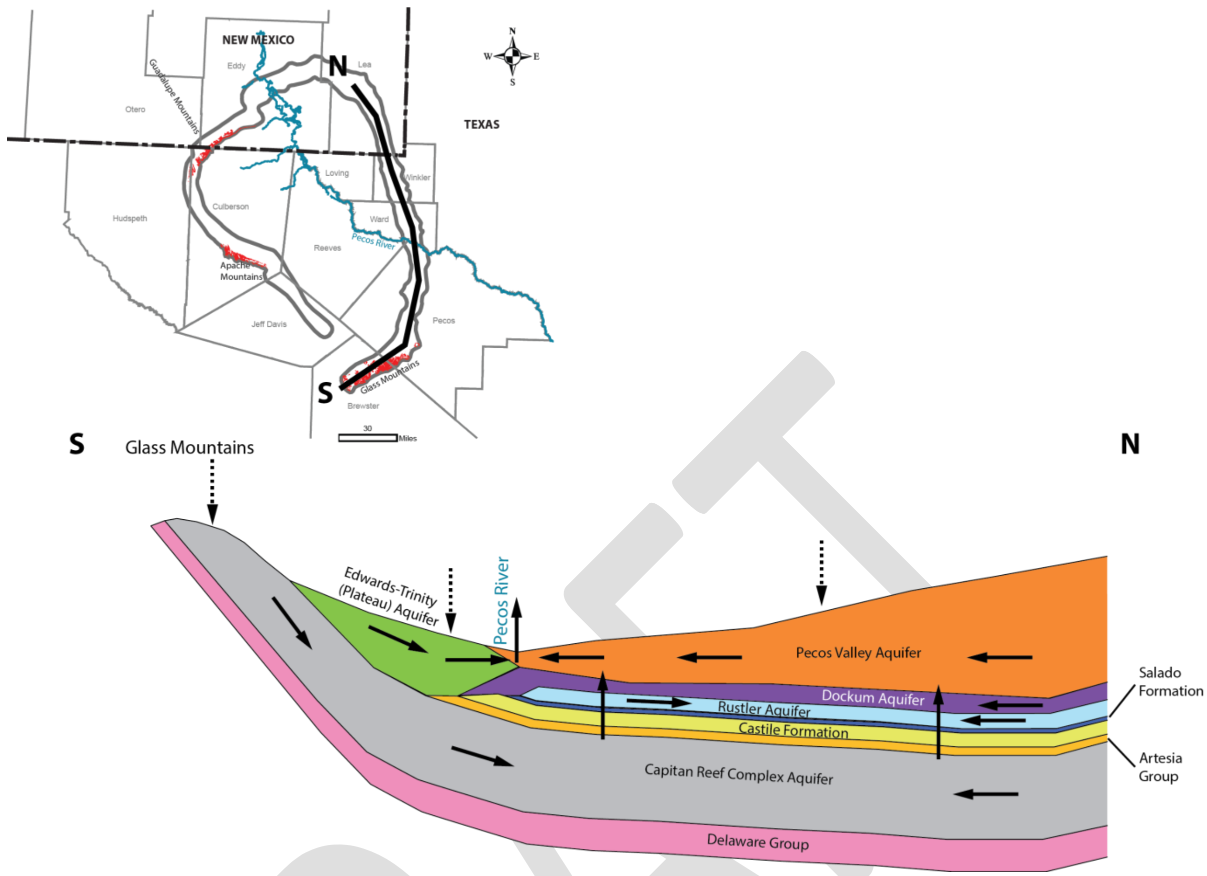
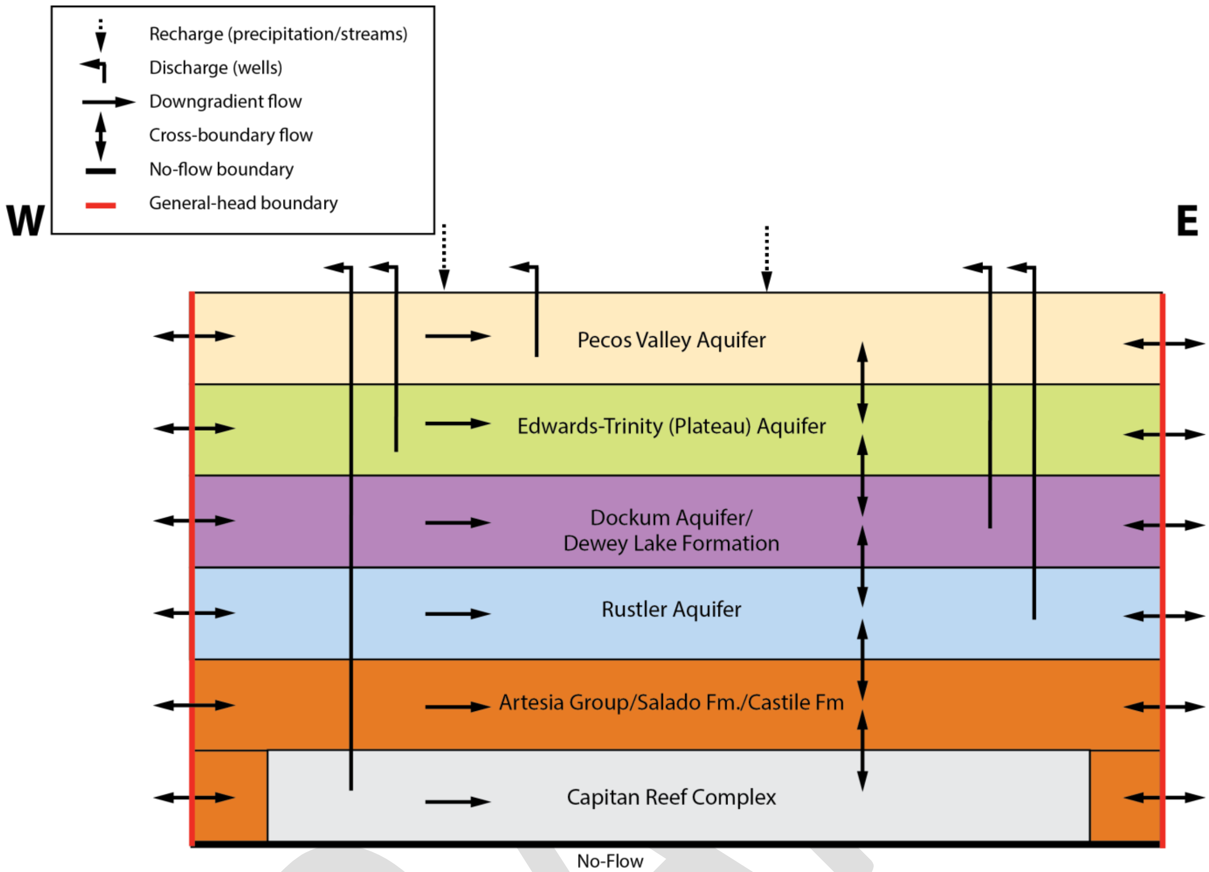
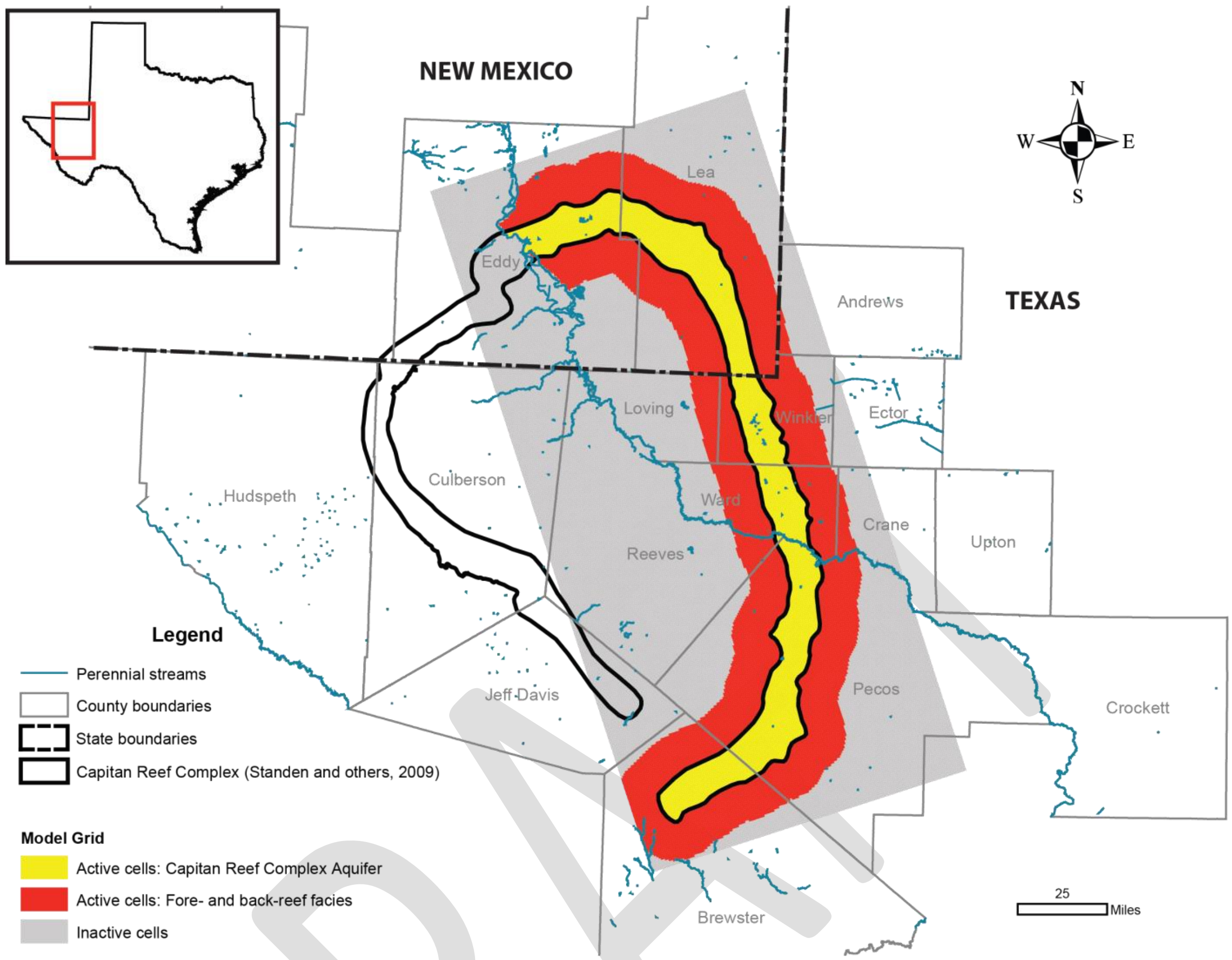


Figure 5.0.1 Schematic cross-section through the Capitan Reef Complex Aquifer Groundwater Availability Model study area.



(A)

Figure 5.0.2 Conceptual groundwater flow model for the Capitan Reef Complex Aquifer Groundwater Availability Model. (A) cross-sectional view and (B) map view.



(B)

Figure 5.0.2 (continued).

6.0 REFERENCES

Angle, E. S., 2001, Hydrogeology of the Salt Basin: *in* Mace, R. E., Mullican, W. F., Angle, E. S. eds., Aquifers of west Texas: Texas Water Development Board Report 356, p. 232-247.

Armstrong, C. A. and McMillion, L. G., 1961, Geology and ground-water resources of Pecos County, Texas: Texas Board of Water Engineers Bulletin 6106, Volumes 1 and 2, 241 and 295 p.

Ashworth, J. B., 1990, Evaluation of ground-water resources in parts of Loving, Pecos, Reeves, Ward, and Winkler counties, Texas: Texas Water Development Board Report 317, 51 p.

Barnes, V. E., Hartmann, B. M., and Scranton, D. F., 1968, Geologic atlas of Texas, Van Horn-El Paso sheet: Bureau of Economic Geology, The University of Texas, Austin, scale 1:250,000.

Barroll, P., Jordan, D., and Ruskauff, G., 2004, The Carlsbad area groundwater flow model: Prepared by the New Mexico Office of the State Engineer with assistance from INTERA Incorporated, 240 p.

Beach, J. A., Ashworth, J. B., Finch, S. T., Jr., Chastain-Howley, A., Calhoun, K., Urbanczyk, K. M., Sharp, J. M., Jr., and Olson, J., 2004, Groundwater availability model for the Igneous and parts of the west Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) Aquifers: Report prepared for the Texas Water Development Board.

Bebout, D. G., and Kerans, C., 1993, Guide to the Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains National Park, West Texas: The University of Texas at Austin, Bureau of Economic Geology Guidebook 26, 48 p.

Berger, D. L., Halford, K. J., Belcher, W. R., and Lico, M. S., 2008, Technical review of water resources investigations of the Tule Desert, Lincoln County, southern Nevada: United States Geological Survey, Open-File Report 2008-1354.

Bjorklund, L. J., 1958, Flow analysis of Carlsbad Springs, Eddy County, New Mexico: United States Geological Survey Open-File Report 58-16, 25 p.

Bjorklund, L. J., and Motts, W. S., 1959, Geology and water resources of the Carlsbad area, New Mexico: United States Geological Survey Open-File Report 59-9, 322 p.

Boghici, R., and Van Broekhoven, N. G., 2001, Hydrogeology of the Rustler Aquifer, Trans-Pecos Texas: *in* Mace, R. E., Mullican, W. F., Angle, E. S. eds., Aquifers of west Texas: Texas Water Development Board Report 356, p. 207-225.

Brackhill, R. M., and Gaines, J. C., 1964, El Capitan source water system: Journal of Petroleum Technology, v. 16, p. 1351-1356.

Brown, E., 1997, Water quality in the Capitan Reef Aquifer: Texas Water Development Board Hydrologic Atlas No. 8.

Brune, G., 2002, Springs of Texas, Volume I, Second Edition: Texas A&M University Press, College Station, Texas, 566 p.

Chowdhury, A. H., Ridgeway, C., and Mace, R. E., 2004, Origin of the waters in the San Solomon Spring System, Trans Pecos Texas: *in* Mace, R. E., Angle, E. S., and Mullican, W. F., III eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 315-344.

Christian, B., and Wuerch, D., 2012, Compilation of Results of Aquifer Tests in Texas: Texas Water Development Board Report 381, 106 p.

Clark, I. D., and Fritz, P., 1997, Environmental isotopes in hydrogeology: Lewis Publishers, Boca Raton, Florida, 328 p.

Cooper, H. H., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well history: Transactions of the American Geophysical Union, v. 2, p. 526-534.

Cox, E. R., 1967, Geology and hydrology between Lake McMillan and Carlsbad Springs, Eddy County, New Mexico: United States Geological Survey Water Supply Paper 1828, 48 p.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, p. 436-468.

Darling, B. K., 1997, Delineation of the Ground-Water Flow Systems of the Eagle Flat and Red Light Basins of Trans-Pecos Texas: unpublished dissertation, University of Texas at Austin, 179 p.

Ewing, J. E., Jones, T. L., Yan, T., Vreugdenhil, A. M., Fryar, D. G., Pickens, J. F., Gordon, K., Nicot, J-P., Scanlon, B. R., Ashworth, J. B., and Beach, J., 2008. Groundwater availability model for the Dockum Aquifer: Contract report prepared for the Texas Water Development Board, 508 p.

Ewing, J. E., Kelley, V. A., Jones, T. L., Yan, T., Singh, A., Powers, D. W., Holt, R. M., Sharp, J. M., Jr., 2012, Groundwater availability model report for the Rustler Aquifer: Contract report prepared for the Texas Water Development Board, 454 p.

Finch, S. T., Jr., and Armour, J., 2001, Hydrogeologic analysis and ground water flow model of the Wild Horse Flat area, Culberson County, Texas: Consultant report prepared for Culberson County Groundwater Conservation District by John Shomaker and Associates, Inc. 37 p.

Finch, S. T. and Bennett, J.B., 2002, Hydrogeology evaluation of the northern part of Culberson County Groundwater Conservation District, Culberson County, Texas: Consultant report prepared for Culberson County Groundwater Conservation District by John Shomaker and Associates, Inc., 24 p.

Fontes, J. C., and Olivry, J. C., 1977, Gradient isotopique entre 0 et 4000m dans les précipitations du Mont Cameroun: Comptes Rendus Réunion Annuelle Sciences de la Terres, Société Géologique Française, Paris, no. 4, p. 171.

Fontes, J. C., 1980, Environmental isotopes in groundwater hydrology, *in* P. Fritz, and J. C. Fontes (eds.), Handbook of environmental isotope geochemistry, Elsevier, New York, v. 1, Ch. 3, p. 75-140.

Garber, R. A., Grover, G. A., and Harris, P. M., 1989, Geology of the Capitan Shelf Margin—subsurface data from the northern Delaware Basin: *in* Harris, P. M., and Grover, G. A., eds., Subsurface and outcrop examination of the Capitan Shelf Margin, northern Delaware Basin: Society of Economic Paleontologists and Mineralogists, SEPM Core Workshop no. 13, p. 3-269.

George, P. G., Mace, R. E., and Petrossian, R., 2011, Aquifers of Texas: Texas Water Development Board Report 380, 182 p.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D., 2002, The national elevation dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, p. 5–11

Gonfiantini, R., 1985, On the isotopic composition of precipitation in tropical stations: Acta Amazonica, v. 15, no. 1-2, p. 121-139.

Gutentag, E. D., Heimes, F. J., Krothe, N. C., Luckey, R. R., and Weeks, J. B., 1984, Geohydrology of the High Plains Aquifer In Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: United States Geological Survey Professional Paper 1400-B, 63 p.

Harris, A. G., Tuttle, E., and Tuttle S. D. 1997, Geology of national parks, Fifth edition: Iowa Kendall/Hunt Publishing, 554 p.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey Professional Paper 446, 69 p.

Heitmuller, F. T., and Reece, B. D., 2003, Database of historical documented springs and spring measurements in Texas: United States Geological Survey, Open-File Report 03-315.

Hibbs, B. J., and Darling, B. K., 1995, Environmental isotopes and numerical models for understanding aquifer dynamics in southwestern basins: *in* Cleveland, T. G., ed., Advances in the development and use of models in water resources: Houston, Texas, p. 195-201.

Hibbs, B. J., Darling, B. K., and Jones, I. C., 1998, Hydrogeologic regimes of arid-zone aquifer beneath low-level radioactive waste and other waste repositories in Trans-Pecos, Texas and northern Chihuahua, Mexico: *in* Van Brahana, J., Eckstein, Y., Ongley, L. K., Schneider, R., and Moore, J. E. eds., Gambling with groundwater—physical, chemical and biological aspects of aquifer-stream relations: Proceedings of the Joint Meeting of the XXVIII Congress of the International Association of Hydrogeologists and the Annual Meeting of the American Institute of Hydrologists, Las Vegas, Nevada, USA, 28 September – 2 October, 1998, p. 311-322.

Hill, C. A., 1996, Geology of the Delaware Basin Guadalupe, Apache, and Glass Mountains, New Mexico and Texas: Permian Basin Section-SEPM Publication No. 96-39, 480 p.

Hill, C. A., 1999, Reevaluation of the Hovey Channel in the Delaware Basin, West Texas: American Association of Petroleum Geologists Bulletin, v. 83, no. 2, p. 277-293.

Hill, C. A., 2006, Geology of the Guadalupe Mountains: an overview of recent ideas: *in* Land, L., Lueth, V. W., Raatz, W., Boston, P., Love, D. L., eds. New Mexico Geological Society Guidebook, 57th Field Conference, Cave and Karst of Southeastern New Mexico, p. 145-150.

Hiss, W. L., 1973, Capitan aquifer observation well network, Carlsbad to Jal, New Mexico: New Mexico State Engineer Technical Report 38, 76 p.

Hiss, W. L., 1975, Stratigraphy and ground-water hydrology of the Capitan aquifer, southeastern New Mexico and western Texas: University of Colorado Department of Geological Sciences, Ph.D. Dissertation, 396 p.

Hiss, W. L., 1980, Movement of ground water in the Permian Guadalupian aquifer systems, southeastern New Mexico and western Texas: New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos Region, p. 289-294.

Holt, R. M., and Powers, D. W., 1990a, Geotechnical activities in the air intake shaft (AIS): United States Department of Energy, DOE/WIPP 90-051, Carlsbad, New Mexico.

Holt, R. M, and Powers, D. W., 1990b, Halite sequences within the late Permian Salado Formation in the vicinity of the Waste Isolation Pilot Plant: *in* Powers, D. W., Holt, R. M., Beauheim, R. L., and Rempe, N., eds., Geological and hydrological studies of evaporites in the northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP): Geological Society of America, Dallas Geological Society, Guidebook 14, p. 45-78.

Holt, R. M., and Powers, D. W., 2011, Synsedimentary dissolution pipes and the isolation of ancient bacteria and cellulose: Geological Society of America Bulletin, published online February 22, 2011.

Huff, G. F., 1997, Summary of available hydrogeologic data collected between 1973 and 1995 and information on all permeability data and aquifer tests for the Capitan Aquifer, Eddy and Lea counties, New Mexico: United States Geological Survey Open-File Report 97-370, 39 p.

Hutchison, W. R., 2008, Preliminary groundwater flow model: Dell City area, Hudspeth and Culberson counties, Texas: El Paso Water Utilities Hydrogeology Report 08-01, 435 p.

Hutchison, W. R., Jones, I. C., and Anaya, R., 2011, Update of the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers of Texas: Texas Water Development Board unpublished report, 60 p.

INTERA Incorporated and Cook-Joyce, Incorporated, 2012, Ferrovial Odessa desalination plant: Unpublished report prepared for Ferrovial Agroman US Corp., 60 p.

INTERA Incorporated, 2013, Estimation of recharge in the Glass Mountains: *in* Hydrogeologic impact assessment report, Ochoa Mine project: Prepared for Intercontinental Potash Corporation, 9 p.

Jackson, J. A., 1997, Glossary of geology: American Geological Institute, Alexandria, VA, 769 p.

Jones, I. C., 2001, Cenozoic Pecos Alluvium Aquifer: *in* Mace, R. E., Mullican, W. F., Angle, E. S. eds., Aquifers of west Texas: Texas Water Development Board Report 356, p. 120-134.

Jones, I. C., 2004, Cenozoic Pecos Alluvium Aquifer: *in* Mace, R. E., Angle, E. S., and Mullican, W. F., III, eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 133-148.

Jones, I. C., 2008, Investigating Recharge in Arid Alluvial Basin Aquifers: The Pecos Valley Aquifer, Texas: Gulf Coast Association of Geological Societies Transactions, v. 58, p. 489-500.

King, P. B., 1930, The geology of the Glass Mountains, Texas, Part 1, Descriptive Geology: Bureau of Economic Geology, The University of Texas Bulletin 3038, p. 128-146.

King, P. B., 1937, The geology of the Marathon region, Texas: United States Geological Survey Professional Paper 187, 148 p.

King, P. B., 1948, Geology of the southern Guadalupe Mountains, Texas: U. S. Geological Survey Professional Paper 215, 183 p.

LaFave, J. I., 1987, Groundwater flow delineation of trans-Pecos Texas: The University of Texas at Austin, unpublished M. A. thesis, 159 p.

LaFave, J. I., and Sharp, J. M., 1990, Origins of ground water discharging at the springs of Balmorhea: *in* Kreitler, C. W., and Sharp, J. M., editors, Hydrogeology of trans-Pecos Texas: Bureau Economic Geology Guidebook No. 25, The University of Texas at Austin, pp. 91–100.

Larkin, T. J., and Bomar, G. W., 1983, Climate atlas of Texas: Texas Water Development Board Report LP 192, 157 p.

Leighty and Associates, 2001, Automated IFSAR terrain analysis system: Sponsored by the Defense Advanced Research Projects Agency, Contract no. DAAH01-98-C-R148, http://www.agc.army.mil/publications/ifsar/lafinal08_01/cover/cover_frame.htm.

McGowen, J. H., Granata, G. E., and Seni, S. J., 1979, Depositional framework of the lower Dockum Group (Triassic) – Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 97, 60 p.

Melim, L. A. and Scholle P. A., 1999, Diagenesis of the Capitan Formation fore-reef facies (Permian, West Texas and New Mexico): *in* Geologic framework of the Capitan Reef: Society for Sedimentary Geology (SEPM) Special publication No. 65, p. 193-210.

Motts, W. S., 1968, The control of groundwater occurrence by lithofacies in the Guadalupian reef complex near Carlsbad, New Mexico: Geological Society of America bulletin, v. 79, p. 283-298.

Myers, B. N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Development Board Report 98, 532 p.

National Climate Data Center, 2011, Data and Products, Climate Data Inventories: Website http://www.ncdc.noaa.gov/oa/climate/climateinventories.html, accessed 2011.

New Mexico Energy, Minerals and Natural Resources Department, 2012, Oil and gas well database, accessed 2012.

Nicot, J. P., Hebel, A. K., Ritter, S. M., Walden, S., Baier, R., Galusky, P., Beach, J., Kyle, R., Symank, L. and Breton, C., 2011, Current and Projected Water Use in the Texas Mining and Oil and Gas Industry: Bureau of Economic Geology, prepared for the Texas Water Development Board, Contract Report 0904830939, 357 p.

Nicot, J. P., Reedy, R. C., Costley, R. A., and Huang, Y., 2012, Oil & Gas Water Use in Texas: Update to the 2011 Mining Water Use Report: Bureau of Economic Geology, Unpublished report prepared for the Texas Oil and Gas Association, 97 p.

Oregon State University, 2006a, United States average monthly or annual maximum precipitation, 1971-2000: The PRISM Climate Group at Oregon State University. Website http://prism.oregonstate.edu/products/viewer.phtml?file=/pub/prism/us_30s/graphics/ppt/Normals/us_ppt_1971_2000.14.png&year=1971_2000&vartype=ppt&month=14&status=final, accessed August 2012.

Oregon State University, 2006b, United States average monthly or annual maximum temperature, 1971-2000: The PRISM Climate Group at Oregon State University. Website http://prism.oregonstate.edu/products/viewer.phtml?file=/pub/prism/us_30s/graphics/tmax/Normals/us_tmax_1971_2000.14.png&year=1971_2000&vartype=tmax&month=14&status=final, accessed August 2012.

Pearson, D. K., 2007, Geologic database of Texas—Project summary, database contents, and user's guide: Prepared for the Texas Water Development Board by the United State Geological Survey, 22 p.

Railroad Commission of Texas, 2012, Oil and gas well database, accessed 2012.

Richey, S. F., Wells, J. G., and Stephens, K. T., 1985, Geohydrology of the Delaware Basin and vicinity, Texas and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 84-4077, 99 p.

Scholl, M. A., Ingebritsen, S. E., Janik, C. J., and Kauahikaua, J. P., 1996, Use of precipitation and groundwater isotopes to interpret regional hydrology on a tropical volcanic island: Kilauea volcano area, Hawaii: Water Resources Research, v. 32, p. 3525-3537.

Sharp, J. M., Jr., 1989, Regional ground-water systems in northern Trans-Pecos Texas, *in* Dickerson, P.W., and Muehlberger, W.R., eds., Structure and stratigraphy of Trans-Pecos Texas: American Geophysical Union Field Trip Guidebook T317, p. 123–130.

Sharp, J. M., Jr., 2001, Regional groundwater flow systems in Trans-Pecos Texas, *in* Mace, R. E., Mullican, W. F. III, and Angle, E. S., editors, Aquifers of west Texas: Texas Water Development Board, Report 356, p. 41-55.

Spatial Climate Analysis Service, 2004, Near-real-time monthly high-resolution precipitation climate data set for the conterminous United States (2.5-arc minute 1971-2000 average monthly precipitation grids for the conterminous United States): Corvallis, OR, Spatial Climate Analysis Service, Oregon State University, arc grid file, http://www.ocs.oregonstate.edu/prism/, accessed October 2008.

Standen, A., Finch, S., Williams, R., Lee-Brand, B., and Kirby, P., 2009, Capitan Reef Complex structure and stratigraphy: Prepared for the Texas Water Development Board, Contract 0804830794, 71 p.

Stone, D. B., Moomaw, C. L., and Davis, A., Estimating recharge distribution by incorporating runoff from mountainous areas in an alluvial basin in the Great Basin region of the southwestern United States: Groundwater, v. 39, no. 6, p.807-818.

Texas Department of Water Resources, 1978, Geohydrology of Major Johnson Springs and Carlsbad Springs, New Mexico: Texas Department of Water Resources Limited Printing Report 23, 44 p.

Texas Parks and Wildlife Department, 2012, Wildscape: Plant guidance by ecoregion: website http://www.tpwd.state.tx.us/huntwild/wild/wildlife_diversity/wildscapes/ecoregions/, accessed August 2012.

Texas Water Development Board, 2012a, Precipitation and Lake Evaporation Data for Texas: website http://midgewater.twdb.texas.gov/Evaporation/evap.html, accessed August 2012.

Texas Water Development Board, 2012b, Well information/groundwater data: website http://www.twdb.state.tx.us/GwRD/waterwell/well_info.asp, accessed October 2012.

Texas Water Development Board, 2012c, Water use survey: website http://www.twdb.texas.gov/waterplanning/waterusesurvey/index.asp, accessed February 2013.

Thomas, H. E., 1963, Causes of Depletion of the Pecos River in New Mexico: United States Geological Survey, Water-Supply Paper 1619-G, 14 p.

Uliana, M. M., 2001, The Geology and Hydrogeology of the Capitan Aquifer—A Brief Overview, *in* Mace, R. E., Mullican, W. F., and Angle, E. S., eds., Aquifers of west Texas: Texas Water Development Board, Report 356, p. 153-166.

Uliana, M. M., and Sharp, J. M., Jr., 2001, Tracing regional flow paths to major springs in Trans-Pecos Texas using geochemical data and geochemical models: Chemical Geology, v. 179, no. 1-4, p. 53–72.

United States Department of Commerce, 2013, TIGER/Line shapefiles technical documentation: Prepared by the United States Census Bureau, 135 p.

United States Environmental Protection Agency, 2011a, Primary distinguishing characteristics of Level III ecoregions of the continental United States: website http://www.epa.gov/wed/pages/ecoregions/na_eco.htm#Level III, accessed August 2012.

United States Environmental Protection Agency, 2011b, Level II and IV Ecoregions of the Continental United States: website http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm, accessed August 2012.

United States Geological Survey, 2002, Physiographic divisions of the conterminous U.S.: website http://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml#stdorder.

United States Geological Survey, 2012a, USGS groundwater data for the Nation: website http://waterdata.usgs.gov/nwis/gw, accessed 2012.

United States Geological Survey, 2012b, USGS surface-water data for the Nation: website http://waterdata.usgs.gov/nwis/sw, accessed 2012.

Veni, G., 1991, Delineation and preliminary hydrogeologic investigation of the Diamond Y Spring, Pecos County, Texas: George Veni & Associates, unpublished report, San Antonio, Texas, p.

Vogelmann, J. E., Sohl, T., and Howard, S. M., 1998a, Regional characterization of land cover using multiple sources of data: Photogrammetric Engineering & Remote Sensing, v. 64, no. 1, p. 45-47.

Vogelmann, J. E., Sohl, T., Campbell, P. V., and Shaw, D. M., 1998b, Regional land cover characterization using Landsat thematic mapper data and ancillary data sources: Environmental Monitoring and Assessment, v. 51, p. 415-428.

Wermund, E. G., 1996, Physiography of Texas: The University of Texas at Austin, Bureau of Economic Geology

White, D. E., 1971, Water resources of Ward County, Texas: Texas Water Development Board Report 125, 219 p.

Wilson, J. L., and Guan, H., 2004, Mountain-block hydrology and mountain-front recharge: *in* Hogan, J. F., Phillips, F. M., and Scanlon, B. R., eds., Groundwater recharge in a desert environment: the southwestern United States: American Geophysical Union, Water Science and Application Series 9, p. 113-138.

Wood, J., 1965, Geology of the Apache Mountains, Trans-Pecos Texas: University of Texas, Austin, Ph.D. dissertation, 241 p.

Wood, J. W., 1968, Geology of Apache Mountains, trans-Pecos Texas: Geologic Quadrangle Texas Bureau of Economic Geology Map No. 35, scale 1:63,360.